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# Guidelines for Developing Radiation Hardness Assurance Device Specifications

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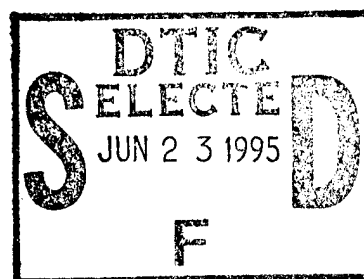
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13. ABSTRACT (Maximum 200 words)  This document discusses how data on the performance of an electronic part should be taken and documented so that it can be easily analyzed and how end-point limits for pass-fail lot acceptance tests should be calculated. Although these guidelines specifically address the problem of radiation hardness, many of the discussions given may be useful more generally to persons responsible for electrical response measurements, the development of procurement specifications, and for system design and the selection of parts for complex electronic systems. A considerable portion of this document addresses the various problems that can appear in data measurements. These discussions emphasize that it is crucial to examine the data carefully to ensure that it is both accurate and representative of the part type which has been sampled for the measurements. The benefits of overstress testing are discussed in Appendix III and a table is given showing how much can be gained for part survivability with such testing.					
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# GUIDELINES FOR DEVELOPING RADIATION HARDNESS ASSURANCE DEVICE SPECIFICATIONS

## 1 SCOPE

1.1 The primary objective of this document is to provide guidelines and easy to follow procedures for the preparation of detailed device specifications for the procurement of microcircuits and semiconductor devices where radiation hardness assurance (RHA) is required. The guidelines are applicable to MIL-M-38510, MIL-S-19500 microcircuit and semiconductor device detailed specifications as well as to other specifications such as source control drawings (SOCD), selected item drawings (SID), specification control drawings (SCD), and standardized military drawings (SMD). Recommended procedures are provided for characterizing the radiation response of a part and for obtaining post-irradiation end-point limits for qualification and lot acceptance tests (LAT).

1.2 Radiation hardness assurance at the piecepart level. These guidelines address radiation response measurement and hardness assurance questions at the piecepart level. In keeping with the present scheme for MIL STD RHA device specifications, which only addresses ionizing radiation dose effects measured at 200, plus or minus 100 rads(Si)/second and displacement damage effects due to neutrons (see TABLE 1 of Section 4.2), these guidelines emphasize these two radiation environments. However, because the addition of dose rate and SEU specifications is now under consideration, brief mention of these two radiation environments is also included. The principles discussed are applicable to both bipolar and MOS silicon transistors and integrated circuits, and to devices made from gallium arsenide and other semiconductor materials. They have, furthermore, been presented in terms of the intrinsic performance characteristics of the part independent of any system in which it may be used. For MIL STD specifications, the levels shown in TABLE 1 of Section 4.2 are used as reference points. The general principles may be applied to system specific requirements.

1.3 LAT end-point limits. The procedures for measuring radiation response characteristics and for calculating LAT end-point limits are discussed in terms of parts whose design and production processes are mature. That is, these guidelines do not attempt to discuss the case where the part is still under development and its characteristics are still undergoing change. It is recognized that this latter case is important and occurs frequently because system designers are interested in obtaining the most advanced parts for their systems. The process of obtaining LAT end-point limits for such parts, however, involves testing and iterative end-point adjustments by the part manufacturer and the system parts engineers and designers which would be difficult to formulate as a set of generalized steps which could be applied to a variety of system needs. Because MIL STD procurements of RHA devices use attribute (LTPD) LAT tests exclusively, the end-point limit discussions here emphasize LTPD tests.

1.4 Low yield devices. If sample costs are affordable, the LAT methods discussed will be performed on samples of the devices themselves. In the case of very large scale integration (VLSI) devices for which only low yields can be achieved, one possible option might be to use devices for LAT which are acceptable from an electrical performance standpoint but do not meet all the normal visual acceptance criteria. Such devices are said to be selected

according to "alternate" visual criteria. Another possible option might be to use test structures for LAT which have been processed on the same wafers as the lot under consideration. By test structures are meant simpler and less expensive microcircuits which have been designed specifically to correlate with the radiation response characteristics and failure levels of the subject VLSI circuit; radiation tests on the test structure can then be used to estimate the performance characteristics of the VLSI circuit. The use of test structures for LAT cannot be recommended until data and experience show definitively that test structure responses correlate reliably with the actual devices.

1.5 Generic Qualification program. A fundamentally different approach to quality assurance, from that based mostly on testing the end product, is now being implemented. An overly simplified description of this approach is to say that it is based on tests which will continuously measure the quality of the starting materials and of the production process itself and allow the material purity and the process to be controlled so that overall quality is not only maintained but is improved with time. This approach, which uses a qualified manufacturers list (QML), is not yet in place and the way in which hardness assurance will be achieved under it has not yet been determined. With respect to the military standard procurement or "JAN" system this approach is also termed "Generic Qualification" (GQ) because it will allow a vendor to qualify a particular production line and then to ship a variety of part types from that line without having to qualify each new part type separately (as is required under the present qualified parts list or QPL scheme). GQ will be important because it is expected to improve radiation response uniformity over extended periods of time. FIGURE 1 shows some of the features of the proposed generic qualification system. A new draft controlling document has recently been issued by RADC which is entitled: MIL-I-38535, "General Specifications for Integrated Circuit Manufacturing." This document includes RHA requirements in all the appropriate sections but does so only in general terms. A "strawman" plan entitled: "Methodology for Including Radiation Hardness Assurance in the Generic qualification Program," is presently undergoing review.

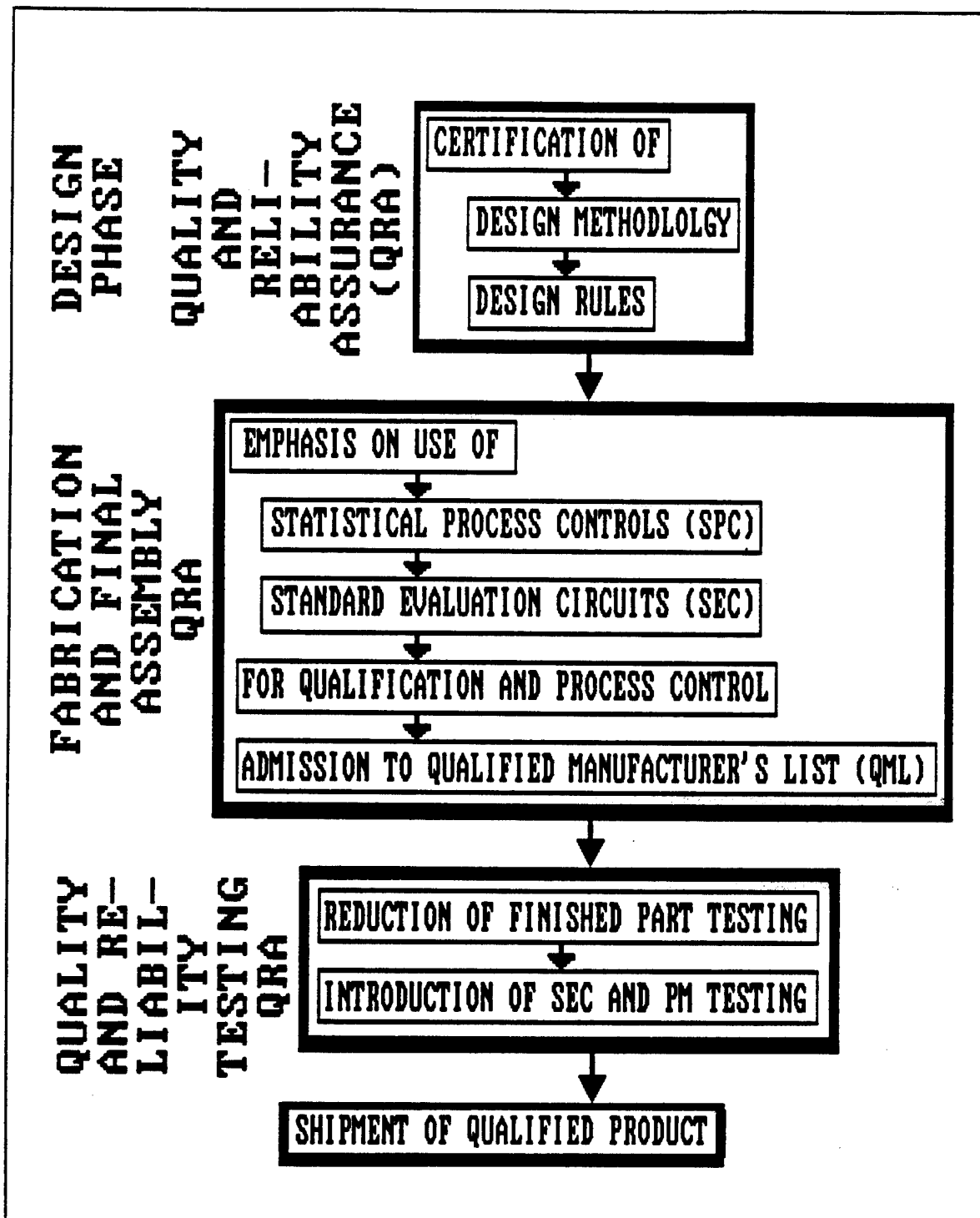


FIGURE 1. Proposed generic qualification system.



## 2 APPLICABLE DOCUMENTS

Although these Guidelines are intended to be used as a "stand alone" document, the following reports and publications may be found useful.

### 2.1 Government Documents.

2.1.1 Specifications, standards, and handbooks. The following specifications, standards and handbooks form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those listed in the issue of the Department of Defense Index of Specifications and Standards (DODISS) and supplement thereto, cited in the solicitation.

#### SPECIFICATIONS

##### MILITARY

DNA-TR-84-220-V1; Hardness Assured Device Specifications for Moderate Requirements, I. Arimura, L. Kolb, and O. R. Mulkey, 18 November 1985

DNA-TR-84-220-V2; Hardness Assured Device Specification a 4K X 1 CMOS/SOS Static RAM, I. Arimura, R. Kennerud, and L. Kolb, 11 February 1985

DNA-TR-81-90; Hardness Assured Device Specifications, I. Arimura, R. Kennerud, and O. Mulkey, 15 July 1982

#### STANDARDS

##### MILITARY

MIL-S-19500; Semiconductor Devices, General Specification for,

MIL-M-38510; Microcircuits, General Military Specification for,

MIL-STD-750; Test Methods for Semiconductor Devices

MIL-STD-883; Test Methods and Procedures for Microelectronics

#### HANDBOOK

##### MILITARY

DNA 5909F; Total-Dose Hardness Assurance Guidelines for Semiconductor Devices, W. E. Price, K. E. Martin, and M. K. Gauthier, 1 February 1982.

DNA 5910F; Piece Part Neutron Hardness Assurance Guidelines for Semiconductor Devices, A. Namenson, E. Wolicki, R. Berger, H. Eisen, J. Ferry, G. Messenger, R. Scace, and H. Schafft, 6 October 1981.

MIL-HDBK-279; Total Dose Hardness Assurance Guidelines for Semiconductor Devices and Microcircuits, 25 January 1985

MIL-HDBK-280; Neutron Hardness Assurance Guidelines for Semiconductor Devices and Microcircuits, 19 February 1985

MIL-HDBK-339 (USAF); Custom Large Scale Integrated Circuit Development and Acquisition for Space Vehicles. 31 July 1984

MIL-HDBK-814; Total Dose and Neutron Hardness Assurance Guidelines for Semiconductor Devices and Microcircuits, J. Ferry, AFWL, to be published.

AFWL-TR-86-26; Guidelines to Hardness Assurance for Nuclear Radiation, Blast and Thermal Effects in Systems with Moderate Requirements, J. M. Ferry, February 1987

DNA-TR-86-29; Dose Rate Hardness Assurance Guidelines, J. Azarewicz, 14 November 1985

DNA-TR-86-38; Hardness Assurance Guideline for MIL-HDBK-339 (USAF) Custom Large Scale Integrated Circuit development and Acquisition for Space Vehicles, R. L. Pease and J. P. Raymond, 27 January 1986

HDL-CR-81-015-1; Design Guidelines for Transient Radiation Effects on Tactical Army Systems, M. Rose, J. Harrity, N. Rudie, K Rasmussen, and J. Halpin, July 1981

HDL-SR-86-1; Nuclear Hardness Assurance and Hardness Maintenance for Army Tactical systems: Part 1. Initial Nuclear radiation, Thermal Radiation, and Air Blast, P. A Trimmer, C. E. Spyropoulos, and L. J. Belliveau

2.1.2 Other Government documents, drawings, and publications. The following other Government publication forms a part of this document to the extent specified herein.

#### PUBLICATIONS

##### FEDERAL

SCR-607; Factors for One-Sided Tolerance Limits and for Variables Sampling Plans, D. B. Owen, Sandia Corp., March 1963

(Available from U.S. Department of Commerce, National Technical Information Service.)

Experimental Statistics, M. G. Natrella, National Bureau of Standards, Handbook 91 (1966)

(Available from the U.S. Government Printing Office, Washington, DC 20402)

2.2 Non-Government publications. The following documents form a part of this document to the extent specified herein.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

1989 Annual Book of ASTM Standards, Volume 12.02, Nuclear, Solar, and Geothermal.

1989 Annual Book of ASTM standards, Volume 10.04, Electronics.

(Application for copies should be addressed to the American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103-1187.)

Statistical Treatment of Damage factors for semiconductor devices, A. I. Namenson, IEEE Trans. Nucl. Sci., NS-26, 4691 (1979)

Hardness Assurance and Overtesting, A. I. Namenson, IEEE Trans. Nucl. Sci., NS-29, 1821 (1982)

Hardness Assurance Statistical Methodology for Semiconductor Devices, I. Arimura and A. I. Namenson, IEEE Trans. Nucl. Sci., NS-30, 4322 (1983)

Proton Upsets in Orbit, W. L. Bendel and E. L. Petersen, IEEE Trans. Nucl. Sci., NS-30, 4481 (1983)

Statistical Analysis of Step Stress Measurements in Hardness Assurance, A. I. Namenson, IEEE Trans. Nucl. Sci., NS-31, 1398 (1984)

Estimating Electrical Parameter End Points for Devices Which Suffer Abrupt Functional Failure During Radiation testing, A. Namenson and I. Arimura, IEEE Trans. Nucl. Sci., NS-32, 4250 (1985)

A Logical Methodology for Determining Electrical End Points for Multilayer and Multiparameter Data, A. Namenson and I. Arimura, IEEE Trans. Nucl. Sci., NS-34, 1726 (1987)

The Effects of Radiation on Electronic Systems, G. Messenger and M. Ash, Van Nostrand Reinhold, 1987.

Ionizing Radiation Effects in MOS Devices and Circuits, T. P. Ma and P. V. Dressendorfer, Wiley, New York, 1989.

### 3. ACRONYMS, DEFINITIONS, AND SYMBOLS

3.1 Acronyms used in this standard. The acronyms used in this standard are defined as follows:

- a. ASTM - American Society for Testing and Materials
- b. DESC - Defense Electronic Supply Center
- c. DNA - Defense Nuclear Agency
- d. DOD - Department of Defense
- e. EPL - End-Point Limits
- f. ERRIC - Electronics Radiation Response Information Center
- g. ESD - Electrostatic Discharge
- h. GQ - Generic Qualification
- i. HA - Hardness Assurance
- j. JAN - Joint Army Navy (military standard)
- k. LAT - Lot Acceptance Tests
- l. LET - Linear Energy Transfer produced when a high energy ionizing particle traverses a solid
- m. LTPD - Lot Tolerance Percent Defective
- n. MIL STD - Military Standard
- o. MIL HDBK - Military Handbook
- p. MOS - Metal Oxide Semiconductor
- q. NASA - National Aeronautics and Space Administration
- r. SPAWAR - Space and Naval Warfare Systems Command
- s. PIPL - Post-Irradiation Parameter Limit, the same as RHEPL in this document
- t. PM - Process Monitor
- u. QA - Quality Assurance

v.	QCI	-	Quality Conformance Inspection
w.	QM	-	Quality Management
x.	QML	-	Qualified Manufacturer's List
y.	QPL	-	Qualified Parts List
z.	QRA	-	Quality and Reliability Assurance
aa.	RADC	-	Rome Air Development Center
ab.	RHA	-	Radiation Hardness Assured or Radiation Hardness Assurance
ac.	RHEPL	-	Radiation Hardness Assurance End-Point Limit
ad.	SCD	-	Specification Control Drawing
ae.	SEC	-	Standard Evaluation Circuit
af.	SEP	-	Single Event Phenomena
ag.	SEU	-	Single Event Upset
ah.	SID	-	Selected Item Drawing
ai.	SMD	-	Standardized Military Drawing
aj.	SOC	-	Source Control Drawing
ak.	SPC	-	Statistical Process Control
al.	STD	-	Standard
am.	TCI	-	Technology Conformance Inspections
an.	TCV	-	Technology Characterization Vehicle
ao.	VLSI	-	Very Large Scale Integration

3.2 General usage for definitions and symbols. To make this report easier to read for those who will need to refer to it only infrequently, an attempt has been made to devise a mathematical notation which is more self-explanatory than the notations used in other recent reports related to hardness assurance. This notation is used in the definitions listed in this section and throughout the rest of the report. As an example of the differences, the present notation uses MEAN(PAR) and GMEAN(PAR) for the measured arithmetic and geometric mean values, respectively, of a parameter; in several other reports an overline on the word

PAR is used to indicate the arithmetic mean value and  $PAR_g$  is used to denote the geometric mean value. Conversions to the other notations, if necessary, should present no difficulties. The following is a list of specific definitions:

- 3.3 ABSORBED DOSE: the absorbed energy usually expressed in rads.
- 3.4 c(lower case): the acceptance number in an LTPD test.
- 3.5 CONFIDENCE LEVEL: the chance of rejecting a lot where there is less than probability P that any part from the lot can pass the test conditions.
- 3.6 DEVICE SPECIFICATION: the contractual document to which an electronic device is either sold or purchased.
- 3.7 DIFFUSION LOT: a set of wafers heated at one time in one diffusion furnace
- 3.8 DOSE: see Ionizing Radiation Dose.
- 3.9 DOSE RATE: rads per second due to ionizing radiation.
- 3.10 EXP(X): Napier's constant, e, to the X-th power. Please note that an exponent can only be a pure number. Therefore, if the notation shows a variable that has a dimension (such as an ionizing radiation dose expressed in rads, for example) as an exponent, it should be understood that the exponent has been made dimensionless by dividing it by a quantity having a value of one but with the same dimensions as the variable in question.
- 3.11 FLUENCE: the accumulated number of irradiating particles per square centimeter.
- 3.12 GOODNESS OF FIT: the degree to which a measured probability distribution fits the assumed distribution; the CHI-square test is commonly used to determine the goodness of fit.
- 3.13 GRAY: 10,000 ergs of absorbed energy per gram; equals 100 rads.
- 3.14 i(lower case): the subscript used to label the i-th device in a sample of devices.
- 3.15 I(upper case): the subscript used to label the I-th lot in a

sample of lots.

- 3.16 IN-FLUX: measurements made on a device while it is being irradiated.
- 3.17 IONIZING RADIATION DOSE: the accumulated absorbed energy in rads or Grays due to ionizing radiation.
- 3.18 JAN parts: JAN parts are listed in the Qualified Products List (QPL) and undergo scheduled periodic audits by the qualifying activity to MIL-M38510 and MIL-STD-883 requirements. The JAN part takes precedence over the Standardized Military Drawing (SMD) part.
- 3.19  $K_{TL}(n, C, P)$ : One-sided tolerance limit. This factor takes into account the uncertainties resulting from small sample size statistics. It is applied to normal distributions as follows: For a sample size  $n$ , if  $MEAN(PAR)$  and  $STDEV(PAR)$  are the measured mean and standard deviation respectively for parameter  $PAR$ , then with confidence  $C$ , there is a probability  $P$ , that future measurements of the parameter  $PAR$  will be less than:
- $$MEAN(PAR) + K_{TL}(n, C, P) * STDEV(PAR)$$
- or larger than:
- $$MEAN(PAR) - K_{TL}(n, C, P) * STDEV(PAR)$$
- 3.20  $LN(X)$ : the natural logarithm of  $X$ . Please note that the argument of a logarithm can only be a pure number. Therefore, if the notation shows a logarithm of a variable that has a dimension (such as an ionizing radiation dose expressed in rads, for example), it should be understood that the argument has been made dimensionless by dividing it by a quantity having a value of one but with the same dimensions as the variable in question.
- 3.21 LOT: the population of parts from which a sample has been taken.
- 3.22 LOT ACCEPTANCE TEST: the testing of a sample of parts from a lot to determine whether the lot is acceptable or

not.

- 3.23 MEAN(X): the arithmetic mean value of X.

$$\text{MEAN}(X) = \frac{1}{n} \sum_{i=1}^n X_i$$

$$\text{e.g. MEAN} [\text{PAR}(\text{RAD})] = \frac{1}{n} \sum_{i=1}^n \text{PAR}_i(\text{RAD})$$

$$\text{e.g. MEAN} [\text{LN}(\text{PAR}(\text{RAD}))] = \frac{1}{n} \sum_{i=1}^n \text{LN}(\text{PAR}_i(\text{RAD}))$$

- 3.24 GMEAN(X): the geometric (or logarithmic) mean value of X.

$$\text{GMEAN}(X) = \text{EXP}(\text{MEAN}(\text{LN}(X)))$$

$$\text{e.g. GMEAN}(\text{PAR}(\text{RAD})) = \text{EXP}(\text{MEAN}(\text{LN}(\text{PAR}(\text{RAD}))))$$

- 3.25 n(lower case): the number of devices in a sample of devices.
- 3.26 N(upper case): the number of lots in a sample of lots.
- 3.27 NON-RHA DEVICES: parts that have not been tested with radiation or parts that fail the radiation test criteria.
- 3.28 STANDARD DEVICES: parts that meet the criteria for military standard (MIL STD or JAN) specifications or for standardized military drawings (SMD).
- 3.29 NON-STANDARD DEVICES: parts that do not meet the criteria for military standard (MIL STD or JAN) specifications or for standardized military drawings (SMD). There are three types of non-standard parts that are used for military



procurement. They are as follows: a) selected item drawings (SID), b) source control drawings (SOCD), and c) specification control drawings (SCD).

- 3.30 NOT-IN-FLUX: measurements made on a device when it is not being irradiated.
- 3.31 OSTL: one sided tolerance limit.
- 3.32 P(upper case): the probability that any part from a lot can pass the test conditions; also called the piecepart survival probability.
- 3.33 PAR<sub>i</sub>: the pre-rad parameter value measured for the i-th device.
- 3.34 PAR<sub>i</sub>(RAD): the post-rad parameter value measured for the i-th device.
- 3.35 PHI(SPEC): the radiation level required in the device specification for lot acceptance tests.
- 3.36 RAD: equals 100 ergs of absorbed energy per gram.
- 3.37 RADIATION HARDNESS ASSURANCE:  
the application of methods and procedures during the procurement of an electronic system to ensure that the radiation response of the system is within known and acceptable limits.
- 3.38 RADIATION HARDNESS MAINTENANCE:  
procedures applied during the deployment phase to ensure that the system's operational procedures, maintenance requirements and aging characteristics maintain the system's hardness. These procedures include tests and inspections.
- 3.39 RADIATION HARDNESS SURVEILLANCE:  
periodic inspection and testing during the lifetime of deployed systems to ensure that, within acceptable tolerances, the radiation responses of the systems remain adequate for mission completion.
- 3.40 RHA DEVICES: parts labelled by letter designators which indicate that the part type has passed lot acceptance tests based on a sample of devices

tested to the device specification radiation levels.

3.41 SELECTED ITEM DRAWING: a specification that is written against any standard part when the system design has a critical requirement not covered by the standard part specification (JAN or SMD). The acronym for this term is SID.

3.42 STANDARDIZED MILITARY DRAWING: a specification written for parts which are listed in MIL-BUL-103 and for which DESC has a certificate of compliance to MIL-STD 883. Approved sources of supply are listed on this drawing. Periodic compliance verification audits are performed on these vendors by the qualifying activity as scheduling allows. When a vendor receives JAN qualification on this part, the part is inactivated for new design and the JAN part takes precedence.

3.43 SOURCE CONTROL DRAWING: a specification that is written when a specific source of supply is required or the part is not covered by a standard part specification (JAN or SMD). The acronym for this term is SOCD.

3.44 SPECIFICATION CONTROL DRAWING: a specification written if a part is not covered by a standard specification (JAN or SMD) and the system does not have any requirements above the vendor's standard part. The acronym for this term is SCD.

3.45 STANDARD DEVICES: parts that meet the criteria for military standard (MIL STD or JAN) specifications or for standardized military drawings (SMD).

3.46 STDEV(X): the standard deviation of X.

$$\text{STDEV (X)} = \left[ \frac{1}{n-1} \sum_{i=1}^n [X_i - \text{MEAN (X)}]^2 \right]^{1/2}$$

$$\text{e.g. STDEV [ PAR (RAD) ]} = \left[ \frac{1}{n-1} \sum_{i=1}^n [\text{PAR}_i(\text{RAD}) - \text{MEAN (PAR (RAD))}]^2 \right]^{1/2}$$

e.g. STDEV [ LN (PAR (RAD)) ] =

$$\left[ \frac{1}{n-1} \sum_{i=1}^n [\text{LN (PAR(RAD))} - \text{MEAN (LN (PAR (RAD)))}]^2 \right]^{1/2}$$

- 3.47 STEP-STRESS TESTING: a series of discrete cumulative irradiations with measurements made after each irradiation increment.
- 3.48 TOTAL DOSE: the accumulated absorbed energy in rads or Grays due to ionizing radiation; not sufficient to determine device response to total ionizing radiation exposure in many types of devices because of time dependent effects.
- 3.49 WAFER LOT: a set of wafers made at the same time and with the same equipment for each processing step. The MIL-M 38510 definition is: a wafer lot consists of microcircuit wafers formed into a lot at the start of wafer fabrication for homogeneous processing as a group, and assigned a unique identifier or code to provide traceability, and maintain lot integrity throughout the fabrication process. MIL-M-38510 allows parallel processing of portions of the wafer lot through multiple machines or process stations on the same certified line provided statistical quality control assures and demonstrates correlations between stations and separately processed portions of the wafer lot.

#### 4. GENERAL CONSIDERATIONS

4.1 Device performance in the radiation environment. Many military and civilian electronic systems must operate reliably in radiation environments. The design of such systems therefore requires that the performance of the individual component semiconductor devices in radiation environments be characterized. The production of the systems then further requires that the parts purchased for production have characteristics at least as good as those on which the design was based. These guidelines discuss how to characterize the performance of semiconductor devices in radiation environments and how to obtain hardness assurance through device procurement specifications based on the characterization data. Applications to an existing system of military standard (MIL STD or JAN) detailed specifications for radiation hardness assured (RHA) devices are emphasized but the discussions may be applied also to other part specifications. Radiation hardness assurance is generally achieved through the use of lot acceptance tests (LAT) in which parts from the lot being purchased are irradiated and tested. Because the MIL STD lot acceptance tests rely largely on pass-fail tests in which a part's performance is compared to a specified end-point limit, these guidelines discuss, specifically, how radiation hardness assurance end-point limits (RHEPL) for such tests should be calculated from the characterization data.

4.1.1 Degrading effects of radiation. The performance of semiconductor devices can be degraded by exposure to radiation which produces ionization or displacement damage. Depending on the type of radiation incident on the device, the rate at which energy is absorbed, and the total accumulated amount of absorbed energy, the device performance can be degraded permanently or temporarily. Examples of temporary degradation are: (a) circuit upset due to the instantaneous photocurrent produced throughout the device by a short pulse of high intensity ionizing radiation or (b) circuit upset due to the collection of charge from a single, local, ionized particle track passing through the device. Upsets due to photocurrents are commonly called dose rate upsets; upsets due to the collection of charge from single ionized tracks are called single event upsets (SEUs). Examples of permanent damage are: (a) device failures due to atomic displacements produced in the semiconductor (usually by neutrons), (b) failures due to trapped charge in insulating layers, which are present in most devices, produced by ionizing radiation, or (c) latchup or burnout produced by photocurrents or by single ionized tracks. Trapped charge effects are sometimes called ionizing radiation dose effects or total dose effects. However, because of time dependent effects after irradiation, specifying the total dose is not considered adequate for describing these effects.

4.1.2 Radiation Hardness Assurance. If nondestructive electrical measurements alone could be used to predict the performance of a part type in a radiation environment, then the hardness assurance problem would be largely solved. One of the cases where such measurements have proven useful has been that of using transistor current gain-bandwidth product,  $f_t$ , measurements to screen out (by requiring  $f_t$  to be above some minimum value) parts which would be

extra sensitive to neutron displacement damage. For ionizing radiation dose, it is necessary to use actual radiation tests to assure the radiation response of a part. In practice, radiation hardness assurance is achieved most commonly through the use of lot acceptance tests (LAT) which are performed on the lots that are being purchased.

4.1.3 Dose rate tests. For the dose rate upsets discussed previously, if sufficient care is used, radiation tests can be non-damaging. Thus parts which have been tested can be used for production. In this case 100 percent of the parts to be used for system production can be tested (screened) and a high degree of assurance can be obtained that the parts will meet system requirements. Caution is still required, because there exists some possibility, especially for complex microcircuits, that the screening tests conducted will not have covered the worst case conditions or exercised all possible paths. Report number DNA-TR-86-29, 14 November 1985, entitled: "Dose Rate Hardness Assurance Guidelines," may be consulted for a detailed discussion of this problem.

4.1.4 Displacement damage, steady state ionization and single event upsets. For displacement damage, steady state ionization effects, and single event upsets, the radiation tests are damaging and it is generally not possible to use the tested parts in the system. The use of damaging radiation tests thus produces the central problem of hardness assurance, namely, that estimates of the survival probability of the parts to be used in the system must be based on statistical inference from a tested sample of parts which are degraded by the tests and therefore cannot be used in the system. This problem is compounded by the fact that production processes can vary so that the currently produced radiation hard parts may not be typical of those that were measured in the past. This case, which is common, has been carefully reviewed by both users and manufacturers of semiconductor devices. The consensus opinion is that, if no additional information is available, the degree of hardness assurance obtained from the detailed specification is limited statistically to that provided by the radiation lot acceptance tests (LAT) or quality conformance inspections (QCI) that are performed (the term QCI is reserved for tests performed by the manufacturer before the lot is approved for shipment).

4.2 MIL STD procurement system. In order to make high reliability hardness assured devices available to designers and manufacturers of systems, the existing MIL STD procurement system was augmented a few years ago to include radiation hardness assured (RHA) semiconductor devices. At the present time, JAN RHA parts are labelled by letter designators which indicate that the part type has passed lot acceptance tests based on a sample of parts tested at the radiation levels shown in TABLE 1.

TABLE 1. Military Standard RHA detailed specifications.

LETTER DESIGNATOR*	HARDNESS ASSURANCE LEVELS	
	IONIZATION EFFECTS**	NEUTRONS***
/	NO RHA	NO RHA
M	$3 \times 10^3$ RAD(SI)	$2 \times 10^{12}$
D	$1 \times 10^4$ RAD(SI)	$2 \times 10^{12}$
R	$1 \times 10^5$ RAD(SI)	$2 \times 10^{12}$
H	$1 \times 10^6$ RAD(SI)	$2 \times 10^{12}$
* FOR MICROCIRCUITS, THE LETTER DESIGNATOR FOR RHA PARTS REPLACES THE SLASH IN THE PART NUMBER; E.G. 38510R291A IN PLACE OF 38510/291A. FOR DISCRETE DEVICES IT IS A SUFFIX, E.G. JANTXVR.		
** AT A DOSE RATE OF 200 RADS(SI)/SEC PLUS OR MINUS 100 RADS(SI)/SEC.		
*** 1 MEV SILICON DISPLACEMENT DAMAGE EQUIVALENT NEUTRON FLUENCE.		

4.3 Lot acceptance tests. Lot acceptance tests (LAT) are used in the military standard (MIL STD) system for determining whether a production lot is of high enough quality so that it can be shipped by the vendor. The tests are of a statistical nature and fall into two general categories: a) attribute tests and b) variables tests.

4.3.1 Attribute tests are the tests most often used in the MIL STD procurement system. For this reason, these guidelines will be directed at the use attribute tests for lot acceptance. Variables tests, on the other hand, are often used for qualifying and accepting system production parts and, for such use, may depend on the particular hardness assurance and derating procedures that the given system is using. Variables tests, therefore, more properly should be discussed as part of a system hardness assurance guideline document and, for that reason, are not discussed in detail here.

4.3.1.1 Advantages and disadvantages of attribute tests. An advantage of the attribute tests is that the data collection and analysis are simple and relatively inexpensive. A further important advantage is that the test is distribution free (i.e. no assumptions are required about probability distributions). However, a major drawback is that the tests require inordinately large sample sizes if significant survival probability requirements are imposed. For example, to check with 90% confidence that a lot has at least 99% survivable parts, i.e that the LTPD is 1% or less, it is necessary to test a sample of at least 231 parts with no failures. It is interesting to note that attribute tests can be applied to attributes that can assume more than just the two values of

pass or fail. Acceptance criteria for lots can also be based on a mix of attributes that may be desired (e.g. with confidence C the probability of a given attribute must be between 49.9% and 50.1%).

4.3.1.2 The n/c test. The most common type of attribute test is the so called n/c test where a sample of n parts is tested and if more than c of the parts fail the test then the lot is rejected. The significant test result for each part is the attribute of passing or failing and hence the term attribute test. The usual failure criteria for parts are: a) functional failure or b) deterioration of any critical parameter past an acceptable limit.

4.3.1.3 Multiple sampling. Some attribute tests allow the drawing of extra samples if lots fail on the first try (multiple sampling plans). A common multiple sampling plan used in the MIL STD system, for example, is a test of 11 parts where the lot is passed if there are no failures. Then, if there is exactly one failure, an additional 7 parts may be sampled and tested with no further failures allowed. If there is a total of two or more failures, the original lot is rejected.

4.3.2 Confidence and probability. The results of the MIL STD attribute lot acceptance test are phrased in terms of a confidence C which is the chance of rejecting a lot where there is less than a probability P that any part in the lot can pass the test conditions.

4.3.2.1 Usual confidence and probability. In the MIL STD system, the significance of an n/c attribute test is usually given in terms of 90 percent confidence and a quantity called the lot tolerance percent defective (LTPD) which may be found, for example, in Table B-1 in MIL-M-38510, the general specification for microcircuits. These tests are, therefore, commonly also referred to as LTPD tests. Thus, for example, the LTPD associated with an 11/0 LTPD test may be found in the table to be 20%. An 11/0 LTPD test will therefore provide 90 percent confidence that a lot with 20% defective parts or greater will be rejected. In terms of the probability P mentioned in the preceding paragraph, LTPD equals 1 minus P.

4.3.3 Variables tests. Variables LAT tests measure a post-irradiation parameter and apply statistical analysis using approximate or exact probability distributions to describe the variability of that parameter (hence the term variables). Usually pre-irradiation values are also measured and they often figure in the analysis (e.g. when the quantity of interest is the change in the parameter, sometimes referred to also as the parameter "delta"). Sometimes the variable of concern is the stress to failure.

4.3.3.1 Advantages and disadvantages of variables tests. The major advantage of variables tests is that a high probability requirement may be imposed even if the sample size is only moderate (typically 10-50 parts). A disadvantage is that the measurements and analysis are generally more complex and expensive. The major disadvantage, however, is that assumptions must be made

about the probability distribution governing the failure of parts. If the distribution is very well known, then this technique can yield high probabilities with high confidences. However, it is usually difficult to know the "wings" of the distribution accurately. Therefore, extrapolations to excessively high probabilities (such as 0.999) based on experience with only a few parts must be regarded with skepticism. It is important to note that, for some kinds of electronics effects (e.g. latchup), there is very little reliable information about the nature of the governing probability distribution.

4.3.3.2 Variables tests depend on tolerance limits which must be compared with the given specifications for the parameter or stress. A lot is rejected if the parameter in question deteriorates beyond an acceptable limit (or if the stress to failure is below the required specification). The tolerance limits are chosen such that with confidence C, the probability is at least P that parts will not fail the test. The exact phrasing of the outcome of a variables test is very similar to that for the attribute test, namely:

4.3.3.3 Confidence and probability for variables tests. There is a confidence C of rejecting a lot if there is less than probability P that any part in the lot will meet the specified parameter (or stress) tolerance limit.

4.3.3.4 Lognormal distribution. The most commonly assumed distribution for the testing of electronic parts is the lognormal distribution (in the lognormal distribution it is the logarithm of the quantity that is normally distributed). The normal distribution is also frequently used. Other probability distributions which have been suggested for some circumstances are the Weibull distribution and the extreme value distribution. If enough parts have been tested, the characterization data can be examined, perhaps with a chi-square test, to see which type of distribution fits best.

4.3.3.5 Ramifications to variables tests. As in the case of attribute tests, there are many ramifications to the use of variables tests. In some cases (e.g. step-stress tests) the uncertainty in the measured parameter or stress can be of importance. In other cases a two-sided tolerance limit may be of importance. Because MIL STD device specifications use attribute (LTPD) tests almost exclusively, this document will not address the ways in which variables tests may be used. It should be recognized, however, that, when systems require very high piecepart survival probabilities, variables tests for lot acceptance may become necessary.

4.3.4 Sampling statistics. The word confidence, as used here, refers strictly to sampling statistics and is the chance of rejecting a lot where there is less than a probability P that any part in the lot can pass the test conditions. The general practice is to take this confidence as the confidence that shipments will be acceptable. This latter use of the word confidence is a matter that is being discussed in the still somewhat controversial subject of Bayesian statistics and is beyond the scope of this document. The important point is that the latter confidence may only be approximated and involves



judgmental decisions. A common practice in hardness assurance is to take the sampling statistics confidence as the confidence that accepted parts will survive. This is an approximation which, though usually valid, may sometimes lead to error. Perhaps the best justification for such an approximation is that it is usually not the major factor which limits the accuracy and confidence levels associated with system survivability estimates and risk assessments. Often, a more difficult problem, for example, is simulation fidelity (does the test accurately represent the threat environment that is specified for the system).

4.3.5 Reasonability of risk assessment results. The major point of the above discussions is to show the approximate nature of risk assessment. Excessively high survival probabilities, such as, for example, a survival probability of 0.999999 (so called 6-nines) may be unreliable for a number of reasons. First of all, such numbers can only be obtained from extrapolations based on an exact knowledge of the probability distribution. However, because radiation tests use modest numbers of parts and the parts which are tested cannot be used afterwards, knowledge of the assumed probability distribution is never adequate for such extrapolations. Thus, for example, some accidental occurrence during the production of the parts may, with a probability exceeding 1 minus 0.999999, produce a part which does not fit the probability distribution assumed for the majority of the parts; the presence of such parts cannot be detected with confidence by the sample sizes which are typical of radiation tests. At the 6-nines level also, human errors in making measurements or in handling the parts can become a significant failure mode which is totally outside the assumed causes of part failure.

4.4 Part Characterization. FIGURE 2 shows the major steps by which characterization data is measured and used for calculating the RHA end-point limits (RHEPL) which are then used in the device procurement specification for radiation qualification and lot acceptance tests (LAT). An important point shown in FIGURE 2 is that an objective must be selected for the LAT (or QCI) tests and that the RHA end-point limits (RHEPL) are then calculated to meet that objective (the acronym PIPL, standing for post-irradiation parameter limits, is also used). Thus, for example, the objective could be to set the end-point limits so that, with 90 percent confidence, at least 90 percent of future lots may be expected to pass a 22/0 test. Pre-rad measurements are essential when the change (delta) in the value of a parameter is of greater interest than the absolute value of the parameter. Although they may not be essential when the absolute value of the parameter is the important quantity, they are nevertheless highly desirable. FIGURE 2 and subsequent discussions, therefore, include pre-rad measurements as part of the characterization procedure.

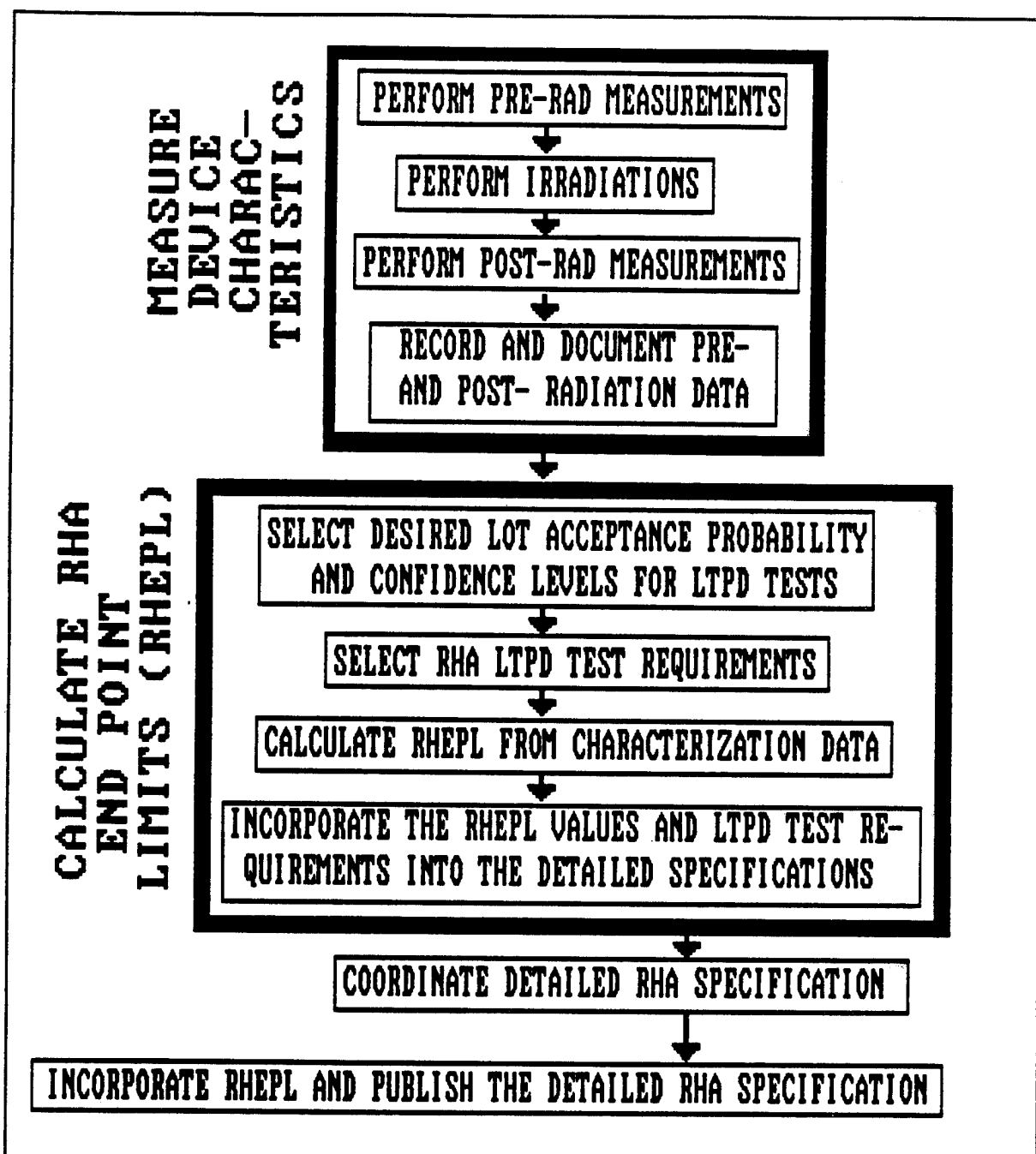


FIGURE 2. Flow diagram for characterizing and specifying the performance of semiconductor devices in a radiation environment.

#### 4.5 Considerations beyond the scope of this document.

##### 4.5.1 Incorporating additional radiation and non-radiation information.

If information is obtained in addition to that provided by the given LTPD test against the RHEPL contained in the detailed device specification, then, for particular system applications, there are several methods by which RHA part survival probabilities can be obtained which are higher than those which correspond to the LTPD test alone. These methods include: the use of the next higher radiation level RHA part, radiation overtests, the use of lot rejection information, the use of variables testing for LAT, and the use of derated parameter values. As an example, most systems manufacturing companies are already familiar with use of derating factors for temperature and aging. Radiation derating factors may be used in much the same way and can thus be fitted into existing practices. These methods properly belong in a document on system level hardness assurance and are not further addressed here.

4.5.2 Further complex questions. The statistical questions involved in hardness assurance and lot acceptance tests range in complexity from cases for which the analysis methods are relatively straightforward to those for which the required formalism is still being developed. In the former instances, these guidelines provide simple step by step procedures that may be used for the analysis of the characterization data. In the latter instances, which are beyond the scope of this document, these guidelines can only suggest approaches which are overly conservative or recommend that statisticians be consulted for less conservative but still valid analyses. In the latter category are cases where the within-lot variations are comparable to lot-to-lot variations (in this case the definition of sample size can become uncertain), cases of combined environments or combined parameters, and cases where not enough data is available. The 1987 paper by Namenson and Arimura, listed in Section 2.2, may be consulted for an approach to multilot and multiparameter data analysis.

## 5 DETAILED REQUIREMENTS

### 5.1 Characterization of piecepart performance in radiation environments.

The first step required for developing a device specification is to characterize the radiation response of the part type in question. Such a characterization for one or more radiation environments requires measurement of its post-irradiation performance and, usually, its pre-irradiation performance as well. The parts, generally, should be characterized through to failure so that the specifications can be written, if necessary, for the maximum capability of the part type. For the present discussion it is assumed that the purpose of the characterization measurements is to support the calculation of parameter end-point limits for qualification and LAT tests in a MIL STD detailed specification and that satisfactory data for the part type in question does not already exist. In this case, the characterization measurements should be such as to permit these calculations to be made for the radiation levels given in TABLE 1 (Section 4.2). Alternatively, the characterization measurements may be required in direct support of a hardened system design or production (custom specifications). In this latter case, the parameters which are measured and the types and fluence levels of the radiations which are used should reflect the system requirements and the specific vendors who are expected to be suppliers for the system. The characterization measurements should also determine the radiation levels required to cause part failure; such information can be important for estimating the design margin when the part is used in some particular application.

To simplify the present discussion, we assume that the average post-irradiation performances of a part type may differ for different manufacturers and, for a given manufacturer, may differ from one lot to another, but that the average radiation response characteristics of a part type, for a given manufacturer, do not significantly change with time. This latter assumption may not always be warranted. It is needed to keep the initial discussion of data measurement and analysis free of the additional complexities that time variations produce.

5.1.1 Documentation of characterization information. Experience has shown that the analysis of radiation data at a future time or by persons other than those who performed the measurements is enormously facilitated by good documentation of the test results. At the same time, a need to analyze previously acquired data or data acquired by others is common. For these reasons and because new measurements are costly, these guidelines recommend that the overall characterization measurements be summarized in a Characterization Report and that the conditions under which the measurements were made be documented in a Test Plan which is included in the characterization report. These documents should furthermore be sufficiently complete so that independent data analyses can be performed on the results contained therein.

5.1.1.1 Characterization Report. The steps required to characterize the performance of a part are shown in FIGURE 3 and discussed in the sections that follow. In general, the discussions identify the decisions that have to be made and the factors that should be considered for each topic. The information developed in these steps is then to be documented in the characterization report.

Some of these items will also be listed in the overall test plan for the measurements. This approach preserves all the information that is developed in the program but keeps the test plan as short as possible. A check-off list of all the steps required for the characterization measurements is given in TABLE 2.

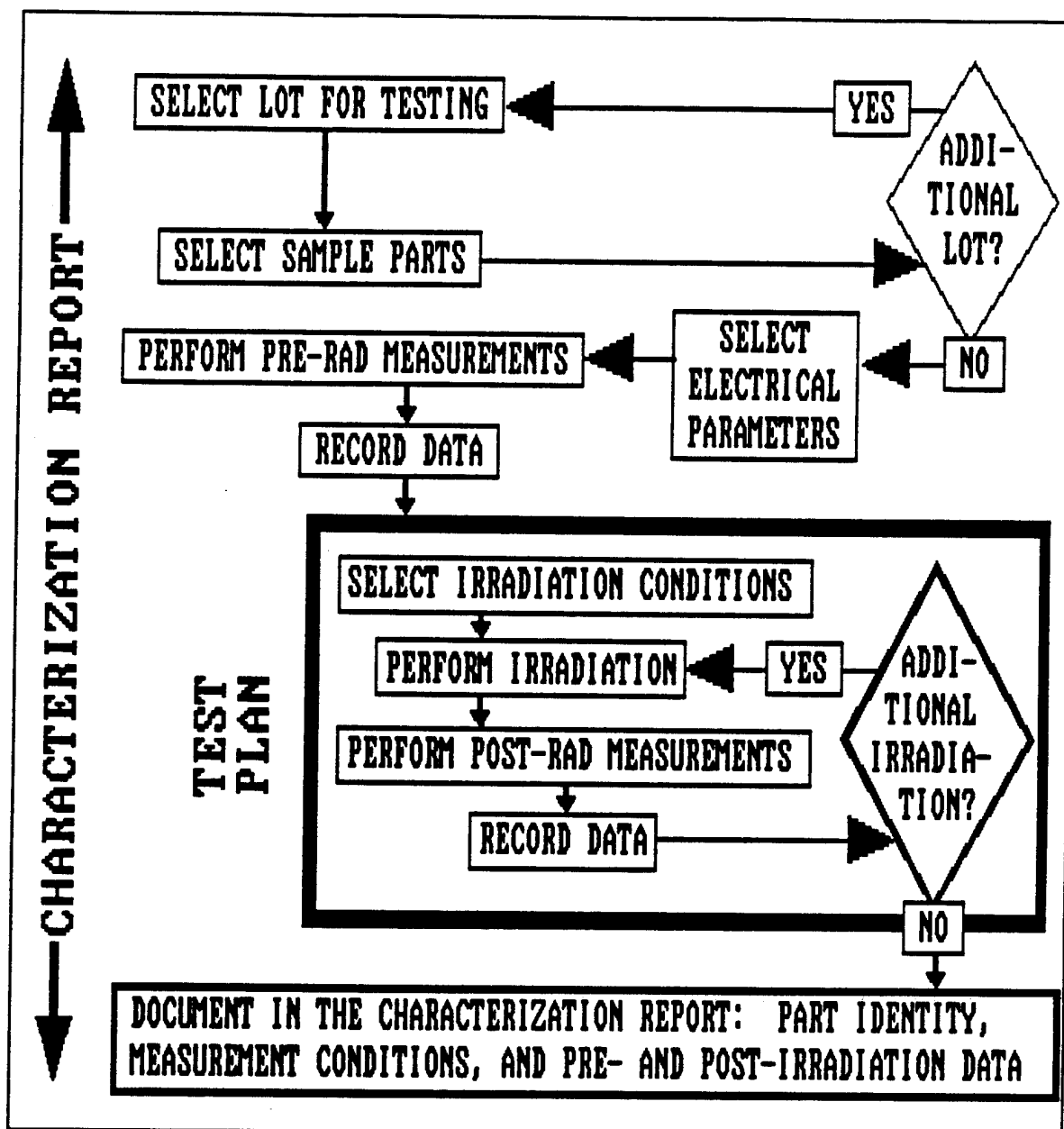


FIGURE 3. Flow diagram for characterizing the performance of semiconductor devices in a radiation environment.

TABLE 2. Step by step procedure for characterization measurements.

<u>Step</u>	<u>Check-Off Item</u>
1.	Start preparing the characterization report. The characterization report will document the information issuing from steps 2 through 25.
2.	Identify the manufacturer.
3.	Specify a way of selecting a random sample.
4.	Specify sample size and distribution in time.
5.	Select the samples; include extra parts for equipment checkout.
6.	Record device identity for each sample device; include traceability to process lot if applicable.
7.	Select radiation environments.
8.	For each radiation environment, select test parameters.
9.	For each parameter, select test conditions; if possible, post rad conditions should be the same as the pre rad conditions. Include location in test cell, bias conditions, etc.
10.	Specify a data format.
11.	Start preparing the test plan. The test plan will be a subsection of the characterization report that will document the information issuing from steps 12 through 24.
12.	Perform pre-rad measurements
13.	Examine measurement results for bad devices or data outliers.
14.	Replace bad device or repeat measurement, whichever is indicated.
15.	Record measurement conditions and results according to the specified data format.
16.	For each radiation environment, select irradiation facility.
17.	For each radiation environment, specify irradiation conditions, and device operating conditions during the irradiation.
18.	Estimate device failure levels including possible abrupt failures.
19.	Specify irradiation step-stress fluences or dose rates to ensure an adequate set of measurements.
20.	As required, check out the irradiation procedure, test fixture, and measuring equipment with spare parts.
21.	Perform radiation exposures and record irradiation conditions.
22.	As required, perform in flux or post radiation measurements.
23.	Examine measurement results for bad devices or data outliers.

5.1.2 Selection of manufacturers. For a selected part type, the potential manufacturers to supply that part for government procurement should be identified. If the part type is already a JAN type, the QPL will serve as a starting point. DESC and the preparing activities for the military standard procurement system (RADC, SPAWAR, and NASA) should be consulted, however, to learn whether additional vendors might be in the process of qualifying for that part type. If the part in question is to be supplied to a standardized military drawing (SMD) or other government specification, then the list of vendors will need to be obtained either from DESC or the cognizant project office.

5.1.3 Selection of random test samples. Sample parts for testing should be selected at random. Because of cost, part availability, schedules, etc., it may not always be practical to obtain an adequate set of samples. The procedures discussed under data analysis in Section 5.2.4, will still apply but will produce increased uncertainties in the results which will reflect the inadequacy of the sample of parts which was used for the characterization. One way of saving costs might be the use of parts which have passed Group A electrical performance tests and alternate visual criteria; this possibility is mentioned for VLSI parts in particular but could have application whenever the cost of sample parts is a limiting factor. It is always advisable that the test parts have gone through burn-in.

5.1.4 Obtaining samples. Once the vendors have been identified, samples of parts should be obtained from each vendor. For each vendor, the samples need to be taken in random fashion from each lot of parts that is being used and the lots need to be selected so that they represent, as accurately as possible, production characteristics. The production variations which are of concern are: a) variations over time, b) variations from one wafer lot to another, c) variations from one wafer to another in a wafer lot, and d) variations of the devices from one region of the wafer to another.

A few extra samples should be obtained to cover the possibility that some devices may, in later measurements, prove to be either bad devices or outliers which will need to be replaced.

5.1.4.1 Recommended sample size. To meet the concerns listed in the previous section, the following quantities, for each vendor and for each radiation environment, are recommended:

- a) Three wafer lots taken at least one month apart.
- b) Five wafers per wafer lot.
- c) Five devices per wafer taken one from each quadrant and one from the center.

A few extra samples should be obtained to cover the possibility that some devices may, in later measurements, prove to be either bad devices or outliers which will need to be replaced. See Section 5.2.4.1.1 for a discussion of bad devices or outliers.

5.1.4.2 Reduced sample sizes. It should be understood that, in cases where the recommended quantities prove to be impractical because of cost or schedule impacts, the vendor may propose reduced sampling requirements. Reduced requirements may be acceptable, for example, where data exists showing the radiation response of the part type in question to be stable and predictable over long periods of time or that the part response will be similar to that of another part.

5.1.4.3 Minimum sample sizes. The sample size recommended in the previous section, for each vendor and radiation environment, is a total of 75 devices. If that number of devices cannot be made available, then reduced sample sizes will have to be considered. Roughly speaking, 25 is the minimum sample size which should be used for a characterization measurement - the more parts the better. For this minimum sample size, the recommendation is that 5 different lots be sampled and that 5 samples per lot be taken. A sample of 25 will at least allow a goodness of fit test to determine whether the part's behavior belongs to a well defined statistical distribution. If the relevant parameters degrade gracefully with radiation and if the probability distribution is known well enough, then 5 or even as few as 3 parts from each lot might be adequate. Larger sample sizes will reduce uncertainties about the nature of the governing probability distribution and will thereby permit better performance estimates for the parts remaining in the population from which the sample was drawn. Sample sizes which are too small may result in characterization data with large statistical uncertainties. These uncertainties can result in overly conservative decisions about how the part should be used or purchased and may lead to costs which will more than undo the savings produced by the small sample size. No simple prescription for selecting sample size can be given. Relevant factors, in addition to part cost, which will affect how large the sample size should be (for each vendor), will include the amount of previous knowledge available about the part and the variability of the part's performance on a single wafer, within a wafer lot, and from lot to lot. If lot to lot variability is large compared to variability within one lot (a not uncommon occurrence) then, in the data analyses that are performed, the sample size effectively becomes the number of lots and not the number of parts tested.

5.1.4.4 Sample sizes in characterization report. The number of samples to be tested, for each vendor, is to be included in the characterization report and in the test plan.

5.1.5 Device identity number and pedigree. Serious problems in analyzing data have also been experienced because the device that was tested was not adequately identified. The information needed to establish an adequate device identity is shown in TABLE 3. This information should be recorded in the characterization report. As discussed in Section 5.1.7.5 on data format, a subset of the TABLE 3 information should be included when the actual test data is recorded and tabulated in the characterization report. It should be recognized that radiation response characteristics, especially for ionizing radiation dose, can be very sensitive to processing conditions. Thus, to the maximum extent practicable, all processing steps and equipment should be



TABLE 3. Device identity information.

- |    |   |
|----|---|
| a. | Device identification number                |
| b. | Generic part number                         |
| c. | JAN part number (if applicable)             |
| d. | Name of the manufacturer                    |
| e. | Lot date code                               |
| f. | Lot number (wafer lot number, if available) |
| g. | Wafer number (if applicable)                |
| h. | Serial number (for each device)             |
| i. | Package type                                |
| j. | Special selection criteria (if applicable)  |

documented for the lot under test. Whenever possible also, the lot under test should be a wafer lot, because a wafer lot is defined as one for which all processing steps are the same and performed with the same equipment. In the case of JAN Class S devices, wafer identity is also available and should be recorded.

5.1.6 Selection of radiation environments. The characterization report and the test plan should identify the radiation environments, such as neutrons; ionizing radiation dose (total dose) and dose rate, also the type of radiation, i.e. whether electrons, gamma rays, protons, etc., and heavy ions or protons (single event upset (SEU)), the radiation facilities, and the levels that will need to be used for the testing. This step should precede that of selecting the test parameters to ensure that no parameters are overlooked which might be especially sensitive to a particular radiation environment. For the two radiation environments of principal interest here, namely neutrons and ionizing radiation dose, the effects are expected to be independent and characterization measurements can be made separately for the two environments. If the effects from two environments are expected to depend on each other, as for example, temperature effects on dose rate induced latchup, or ionizing radiation dose effects on SEU sensitivity, then each part will have to be exposed to both environments. If the given part type is known to be very hard to a particular radiation environment as, for example, an MOS device may be to neutrons, then characterization measurements for that type of radiation may be omitted. Careful consideration should be given, however, to the possibility that intentional or parasitic sensitive elements (e.g. bipolar devices in the MOS example cited) may be present in the device.

5.1.7 Selection of test parameters. All the parameters that are to be measured need to be selected and listed in the test plan. Normally, for JAN parts, the subset of Group A electrical parameters that are known to be sensitive to the selected radiations will be used. In some instances, the change in the value of a parameter is more significant than the absolute value of the parameter. For those cases, the test plan should specify that the change, or delta, in the parameter value be measured.

5.1.7.1 Test conditions and parameters to be recorded. The parameters or circuit functions that need to be measured will have to be identified and listed in the report and in the test plan along with the experimental conditions under which the measurements are to be made. The specified conditions should include both the nominal and the worst case conditions under which each parameter should be measured. They should also include such quantities as, bias voltages, operating frequencies, and ambient temperatures before, during, and after irradiation. For the worst case measurements, the report should contain recommendations on how such conditions may be derived or at least bracketed (circuit analyses may be required to arrive at worst case conditions). This section of the report may also be used to identify, for each parameter that is to be measured, what value of the parameter constitutes device failure. Such definitions are needed in connection with the fluence to failure measurements recommended earlier for permitting estimates of design margin to be made for particular applications. Failure may be either parametric failure, loss of functionality, or degradation to the point where the device can no longer be used.

5.1.7.2 Objectives of the test test conditions and parameters. The selection of test conditions and test parameters will depend on the objectives of the test, time and budget constraints, and, possibly, other factors. For each test, however, the information listed in TABLE 4 should be recorded in the characterization report. As is discussed in Section 5.1.7.5 on data format, a subset of the TABLE 4 information should be included when the actual data is tabulated and recorded in the characterization report. Experience gained by the DNA sponsored Electronic Radiation Response Information Center (ERRIC) is the basis for most of the recommendations contained in these guidelines regarding data requirements and format.

TABLE 4. Pre- and post-irradiation measurement information.

- a. Name and organization of test engineer
- b. List of equipment used for measurements and calibration procedures
- c. Description of test procedures or test standards used
- d. Electrical test date
- e. Test number
- f. List or table of electrical test parameters and corresponding bias conditions; (note that the pre-rad bias conditions should be used for the post-rad measurements)
- g. A complete time history of the individual irradiations and the post-irradiation measurements (especially necessary for ionizing radiation dose (total dose) because of time dependent effects)
- h. Ambient and/or case temperature
- i. Sample size
- j. Electrical measurement results for each parameter
- k. Narrative information

5.1.7.3 The narrative information listed in the TABLE 4 is used to provide a further description of the device and the test conditions required for each test.

5.1.7.4 A partial list of MIL STD symbols for particular device parameters and the corresponding symbols used by ERRIC is given in APPENDIX I. A standard list which all users have agreed to use does not exist for device parameters. As a result, different symbols are sometimes used by different organizations for the same device parameter. ERRIC can receive data labelled in any way and uses a narrative comment as part of the data storage to make sure the device parameter is properly identified. If data processing programs are used for analyzing the behavior of particular parameters, provision should be made for recognizing some limited set of the symbols for the parameter in question in addition to those given in APPENDIX I.

5.1.7.5 Specification of a data format. Although data format would appear to be a simple matter, past experience has shown that severe difficulties can be encountered, particularly with computerized data analysis programs, if a standardized data format is not used to record the data. Because the accumulation of radiation response information in a centralized data bank can

help avoid duplication of such measurements and is therefore highly desirable, the data format recommended here is the one used by ERRIC.

5.1.7.5.1 Definition of a test number in ERRIC. In ERRIC, a unique test number is assigned to both the pre- and post-rad measurements that are made on a single parameter under a single set of bias or operating conditions, for all devices in the sample, and for all the radiation fluences used. The information which is common to a unique test number and which can be used therefore as the heading for that test number is listed in TABLE 5. Pre- and post-rad test results obtained for all the sample devices that are covered by the same heading are then listed under a single test number.

TABLE 5. Example of erric test data.

Test number: <u>1</u> ; Test date: <u>10-21-85</u>				
Type of radiation: <u>neutrons</u> ; Radiation facility: <u>PMI</u>				
Device type: <u>DAC-08</u> ; Manufacturer: <u>ABC</u> ; Lot date code: <u>8429</u>				
Parameter: <u>IREF</u> ; Units: <u>mA</u>				
Test conditions and narrative information:				
a. bit high speed multiplying D/A converter (device description included only for test number 1)				
b. Reference bias current (parameter description)				
c. V+ = 15 V, V- = -15 V				
d. Measured 24 hours after the end of the irradiation.				
<u>MEASUREMENT DATA</u>				
DEVICE		RADIATION LEVEL		
SERIAL	PRE-RAD	2.00E12	6.00E12	1.00E13
NUMBER				
0271	2.00	2.00	2.00	2.00
0272	2.00	2.00	2.00	2.00
....	....	....	....	....

TABLE 6 shows an example of how ERRIC data is recorded.

For test number 2 and subsequent tests made on the same devices and for the same irradiation conditions, the first three lines of the heading need not be repeated. Thus, the data for test number 2 could be recorded as in TABLE 7:

TABLE 6. Information common to a unique test number in erric.

- a. Single type of radiation and corresponding test facility
- b. Single part type
- c. Single manufacturer
- d. Single test date (post-rad)
- e. Single lot date code
- f. Single wafer lot number (if available)
- g. Single parameter measured and associated bias or operating conditions
- h. Narrative information (should include information about the irradiation conditions and time history of the irradiations and the electrical measurements)

TABLE 7. Erric data format for test number 2 in a series.

Test number: 2; Test date: 10-21-85  
 Repeating test information: Same as lines 2 and 3 for test number 1  
 Parameter: IZS; Units: mA  
 Test conditions and narrative information:  
 a. Zero scale current (parameter description)  
 b. V+ = 15V, V- = -15 V.  
 c. Time of measurements referred to the end of the irradiation.

MEASUREMENT DATA

DEVICE	RADIATION LEVEL			
SERIAL	PRE-RAD	2.00E12	6.00E12	1.00E13
NUMBER				
0271	4.20E-5	2.00E-5	6.50E-5	1.67E-4
0272	-2.00E-6	4.70E-5	9.00E-5	2.54E-4
....	....	....	....	....

5.1.8 Test Plan. FIGURE 3 (Section 5.1.1.1) and TABLE 2 (Section 5.1.1.1) show the major steps involved in characterizing the radiation response of a part. Also shown are the steps which are included in the test plan. The test plan should, as a minimum, address the pre-irradiation measurements to be made, the irradiations to be performed, the post irradiation measurements to be made, and, finally, should specify the data documentation requirements and format.

5.1.8.1 Advantages of a good test plan. The development of a detailed test plan is recommended as a way to make characterization measurements efficient. A good test plan will minimize costs by specifying the data set which will meet the objectives of the measurements and by optimizing the use of radiation test facilities and part samples. The test plan should also facilitate subsequent data analysis by specifying a data format which will be easy to use and will protect against inadvertent omission of required data points by providing a check list for the measurements.

5.1.8.2 Pre-irradiation measurements and data examination. If the pre-irradiation characteristics are measured, the measurements should be made according to the conditions listed in TABLE 4 (Section 5.1.7.2) and recorded in the format given in TABLE 6 (Section 5.1.7.5.1) and TABLE 7 (Section 5.1.7.5.1). The data should be examined to make sure that there are no bad measurements, devices or data outliers in the sample. This examination is important to keep bad data from being entered into the report. If bad or anomalous data are taken, this fact together with an explanation of why the data is not being used should be recorded in the characterization report even if the data are not sent to ERRIC or some other data bank. The annual books of ASTM standards, listed in Section 2.2, contain many of the test methods that can be used for making radiation response measurements.

5.1.8.3 Caution should be exercised when devices are handled, particularly with regard to pin alignment in the holding fixture and when the devices are attached to the test circuit. Bias voltages should be off during attachment. ESD handling procedures should be observed for the class of parts being tested.

5.1.8.4 Irradiation conditions. The irradiation conditions and the reasons for selecting them should be discussed in detail in the characterization report and summarized in the test plan. The information to be included in the test plan is listed in TABLE 8. The various questions that need to be addressed in selecting the irradiation conditions are discussed in the sections which follow. For each of the selected radiation environments, the plan should include the test facility selected, the responsible organization and personnel, recommended dosimetry techniques, the maximum fluence or ionizing radiation dose to be reached (whenever possible, the radiation levels should be high enough so that most of the test devices can be made to fail), and whether device measurements will be made "in flux", i.e. while the device is being irradiated, or whether a series of discrete irradiations with measurements following each irradiation will be made. In the latter case, which is sometimes called step stress testing, the test plan should specify the number of irradiations to be made and the ionizing radiation dose or fluence for each irradiation in the series. Because time

TABLE 8. Irradiation conditions.

- a. Name of the radiation test facility.
- b. Name and organization of radiation test engineer
- c. List of dosimeter types and readout equipment
- d. Date of irradiations
- e. Irradiation run number
- f. Number of samples in each irradiation
- g. Placement of samples with respect to the radiation source
- h. Radiation facility operational mode
- i. For each irradiation, flux or dose rate, fluence or ionizing radiation dose, start and stop times, and ambient or device case temperature
- j. Device bias conditions and whether in-flux measurements will be made
- k. Start and stop times for post irradiation measurements, including measurements made during a series of radiation exposures (particularly important for ionizing radiation dose because of the time dependent effects which can occur)

dependent effects can be very important, especially for ionizing radiation dose, a complete time history of the irradiations and the post-radiation or in-flux measurements should be recorded. This time history should include the start and stop times of both the irradiations and the measurements as well as the rate at which the ionizing radiation dose was delivered. The test plan should state, whenever possible, that a standard irradiation test method should be used and give the appropriate reference.

5.1.8.5 Estimates of device failure levels. To reduce costs and to optimize the usefulness of the data obtained, it is important to estimate the expected failure levels for the selected device type and radiation environment before full scale characterization measurements are begun. Device failure will usually be defined as parametric failure but may sometimes be defined as functional failure. In the case of parametric failure it is well known that different failure limits can be defined for different device applications. For the present purpose, engineering judgement should be used to define a failure limit for each parameter being measured. The important point is that the lowest stress level which renders the device unacceptable should be considered as the failure level. Estimates of failure levels will have to be based either on previous experience and data or on measurements on a few parts from the available samples. The steps by which the failure points are estimated should be documented in the characterization report. Because the definition of parametric failure depends on the intended device application, the estimated failure points will only be

approximately correct. They will nevertheless be useful for adjusting the irradiation increments and the total fluences to match the expected device performance. The irradiation increments and the total fluences selected on the basis of the estimated failure points should be listed in the test plan. After the characterization measurements are completed, device failure points can be more accurately defined.

5.1.8.6 Gradual degradation. For devices which degrade gradually as they approach failure, it will generally be useful to measure post-irradiation performance characteristics as a function of accumulated radiation fluence or ionizing radiation dose because such results can be used to interpolate or, in some cases, extrapolate the part's performance to radiation levels other than those used in the tests. For such devices, the number of irradiations and the radiation increments should be made commensurate with the expected failure levels. It is worth noting that a gradual approach to failure may not always be monotonic; sometimes a parameter may first increase with radiation fluence and then subsequently decrease. This behavior means that, in the MIL STD system and for the radiation levels shown in TABLE 1 (Section 4.2), a part type that has been qualified at a higher level may not meet the same RHEPL at a lower level. Qualification at a higher level should therefore not mean, automatically, that the part is also qualified at a lower level unless care is taken to select the RHEPL so that it does not show less degradation at the higher level.

5.1.8.7 Abrupt failure. Some devices give little or no indication that a radiation failure point is being approached, until they fail abruptly; usually abrupt failures occur as loss of functionality. The claim has sometimes been made that there is usually some gradually deteriorating parameter which can be used as a predictor of abrupt failure (e.g. a flip-flop circuit failing functionally when the fanout capability of the circuit, as indicated by the sink current, degrades past a certain point). As a practical matter, however, a device must be considered to fail abruptly when there is no feasible way to pinpoint its failure level by means of interpolation. An estimated failure level is also important for such devices and should be used for selecting the number and increment value for the irradiations such that the abrupt failure point will be narrowly bracketed. Whenever possible, the most desirable measurement is to monitor the device while it is being irradiated to determine the exact stress level where failure occurred. Again, the estimated failure point will have to be based on previous data or on measurements on a limited sample size before full scale characterization measurements are made.

5.1.8.8 Optimum use of radiation facilities. Such factors as the number of devices which can be irradiated at one time, the length of time required for the irradiation, and the length of time required to complete post-irradiation measurements should be considered when an irradiation schedule is being planned. The selected irradiation schedule should then be itemized in the test plan.

5.1.8.8.1 Selection of radiation levels. For each type of radiation and for each estimated device failure level, a series of irradiations should be selected so that data is obtained most efficiently. The lowest level of



radiation should be below that which produces any failures. In general the subsequent irradiation increments will be sizeable fractions of the failure level. If significant non-linear behavior is produced, however, then the location of the non-linear region must be estimated and the radiation increments should be made smaller than they are outside of it. The highest radiation level should be high enough so that all of the tested parts will fail. This selection will not only allow the device specification to be written for the maximum capability of the part type, should that be necessary, but will provide information on how close the part is to failure for a given system application.

5.1.8.8.1.1 Selection of radiation levels and abrupt failure. For step stress measurements and the presence of abrupt failure, the proper selection of radiation stress levels is of particular importance because a bad choice can compromise the measurements. The spacing between stress levels should be as small as feasible. At the very least, care should be taken to assure that the spacings are small compared to the estimated standard deviation of the failure fluences for the parts to be tested. An estimate of this standard deviation may not be easy to obtain. As a first approximation, data on similar parts may be used. If there is no suitable data, smaller than expected spacing may be necessary for the first few parts and then, if costs can be lowered thereby, the spacing for the rest of the parts can be adjusted according to the measured standard deviation. For a complete characterization, the highest stress level must be large enough to drive all the tested parts to failure. Very wide stress levels may require an extra large sample size. Less than four stress levels are unacceptable if abrupt failure of devices is considered a possibility.

5.1.8.9 Efficient use of test samples. The costs of radiation testing and, for some part types, the cost of the parts themselves both provide strong reasons for keeping the number of test parts as low as possible. In these circumstances it is essential that the experiments be specifically planned so that the maximum amount of useful information is obtained from the sample size that is available. Whenever possible, preparations for the actual tests should be conducted on spare and perhaps less expensive parts which are not part of the final sample.

5.1.8.9.1 Selection of exposure sequences. Because most characterization measurements are destructive, a single device is exposed to only one radiation environment and the exposure sequence simply proceeds from low levels to functional or parametric failure. The cases where one device can be used for two radiation environments are those when the dose rate upset threshold measurement, which can be non damaging, is made first and is followed by neutron, gamma ray, or SEU tests. In these cases care must be taken to ensure that the accumulated ionizing radiation dose in the dose rate testing has not appreciably changed the characteristics of the device. The use of one device for two radiation environments is not recommended. It should be considered only when sample costs are so high that every possible way of conserving sample size must be used. Time dependent effects should be considered when a series of exposures is being planned.

5.1.9 Radiation Exposures. Radiation exposures should be made in accordance with the test plan and should contain at least the information listed in TABLE 8 (Section 5.1.8.4). Initial test system checkout, e.g. of test equipment operation, dosimetry, etc., should be accomplished with parts which are less costly and readily available; one possibility is to use parts of the same type as the sample but selected to a less stringent visual criterion. The use of a commercial equivalent device type can also be considered but such use will need to be validated experimentally.

5.1.9.1 Neutron exposures. Neutron exposures can be made either at fast burst reactors or at water moderated reactors. In either case, the dosimetry practices at the selected facility should be checked to make sure that a valid 1 MeV displacement damage (Si) equivalent fluence can be obtained (ref. ASTM standard E722-85). Test method 1017 of MIL STD 883, entitled "Neutron Irradiation" can be used as a guide for the exposure procedure. Short term (of the order of seconds) annealing effects do not have to be evaluated MIL STD part types.

5.1.9.2 Ionizing radiation dose (total dose) exposures. Test method 1019 of MIL STD 883, entitled "Steady State Total Dose Irradiation Procedure," specifies either Co-60 or an electron beam as the radiation source to be used for ionizing radiation dose testing. Ionizing radiation testing can also be performed with Cesium-137 sources and with low energy X-ray sources. If a source other than Co-60 is used, correlation measurements must be performed to effect a comparison with Co-60. High energy electron Linacs are not recommended because of the possibility that the displacement damage which high energy electrons produce may interfere with the measurements. Flash x-ray sources which, typically, deliver the dose at a very high dose rate, are not recommended because the results may be difficult to compare with Co-60. Low energy x-ray sources are not recommended for characterization measurements unless a valid correlation to Co-60 is established.

5.1.9.3. Bias must be applied on the device during the irradiations and the bias conditions must be in accordance with the test plan. If measurements are to be made "in flux," then the test plan should specify these conditions as well. Because time dependent effects can be very important for ionizing radiation dose, a complete time history of the irradiations and the post-radiation or in-flux measurements should be recorded. This time history should include the start and stop times of both the irradiations and the measurements as well as the rate at which the ionizing radiation dose was delivered. A pre-test evaluation of the time dependent effects may be also be necessary to make sure the times used for the irradiations and the measurements will give meaningful results.

5.1.9.4. Transient ionization (dose rate) exposures and measurements. High energy electron Linacs are the facility of choice for dose rate upset measurements. If Flash x-ray machines are used, extra care is required with the dosimetry to make results obtained at one facility comparable to those obtained at another. MIL STDS 1021 on "Dose Rate Threshold for Upset of Digital Microcircuits" and 1023 on "Dose Rate Response of Linear Microcircuits" may be

used as guides. MIL STD 1020 on "Radiation Induced Latchup Test Procedure" is under revision, principally because it does not adequately treat the case of latchup "windows". It can be used for general guidance provided that no interference is expected from this "window" problem.

5.1.9.5 Single event upset irradiations and measurements. Single event upset (SEU) measurements are sufficiently complex so that they should be made in collaboration with one of the several groups in the U.S. that are making such measurements routinely. A full characterization measurement for single event upsets or latchup produced by heavy ions requires that the number of upsets or the latchup in a particular device be measured as a function of the linear energy transfer (LET) of the ion. Heavy ion irradiations are usually performed at Tandem Van De Graaff accelerators but may also be performed at other high energy heavy ion accelerators (ref. ASTM standard F1192 entitled: Standard Guide for the Measurement of Single Event Phenomena Induced by Heavy Ion Irradiation of Semiconductor Devices). For single event upsets induced by protons, a measurement of the number of upsets per unit fluence at a proton energy of 60 MeV or higher should be adequate as an input data point to a theoretical model that can then be used for estimating the total number of device upsets to be expected in some particular proton environment. (ref. Bendel and Petersen, 1983) High energy protons for SEU tests can be obtained from a number of cyclotron accelerators. Laser and Californium-252 techniques are being studied but have not yet advanced to the point where they can be used routinely for SEU characterization measurements.

5.1.10 Post-Irradiation Measurements and Data Examination. The parameters which will be measured after irradiation and the measurement conditions, and the equipment if possible, should be the same as those for the pre-irradiation measurements. TABLE 3 (Section 5.1.5) and TABLE 5 (Section 5.1.7.5.1) list the information required. The test plan will contain the actual parameters to be measured and the corresponding operating conditions. However, the post-irradiation measurement procedure will have to take into account the possibility of time dependent effects. In the case of ionizing radiation dose, time dependent effects can be especially serious and must be evaluated for the device being tested. MIL STD Method 1019 can be used as a guide until an improved method for taking time dependent effects into account is developed. Bias must be applied during the irradiation. Bias may not be necessary at all times after the irradiation but the bias conditions and other measurement conditions and time intervals should be as consistent as possible from one run to another. Bias or shorting conditions on the device between the end of a radiation exposure and the start of electrical measurements should be recorded.

Again, the measurement results should be examined for bad devices or outliers and, appropriate action taken if necessary. This examination is important in preventing bad data from being included in the characterization report and, possibly later, from entering a data base.

5.1.11 Data recording. TABLE 9 gives a summary of the recording requirements for the test plan.

TABLE 9. Summary of data to be recorded in the test plan.

PRE-RAD MEASUREMENT CONDITIONS: Items in Table 4.

IRRADIATION CONDITIONS: Items in Table 8.

POST-RAD MEASUREMENT CONDITIONS: Items in Table 4.

DATA RECORDING: As in Tables 5, Table 6, and Table 7.

5.1.12 Performance Characterization Report. An essential part of any characterization measurement program is to document all the measurement results completely enough so that another investigator can use the results without having to consult the originator. For a variety of reasons, time and funding being principal among them, this task is often not performed adequately. The importance of the documentation task, however, cannot be overemphasized. The hope here is that if the documentation task is made part of the test plan so that it must be included in any checkoff list or, perhaps, in the contract data requirements list that is part of all government contracts, then the results of characterization measurements will be more available to other users in the future than they have sometimes been in the past.

5.1.12.1 Standard data format. The characterization report should use the standard data format discussed in Section 5.1.7.5. The recorded data should include the device identity information listed in TABLE 3 (Section 5.1.5) and the test conditions listed in TABLE 4 (Section 5.1.7.2).

TABLE 10 gives a summary of the recording requirements for the characterization report.

TABLE 10. Summary of information to be recorded in the characterization report.

DEVICE IDENTITY: Items in Table 3 and corresponding discussion

PRE-RAD MEASUREMENT CONDITIONS: Items in Table 4 and corresponding discussion

IRRADIATION CONDITIONS: Items in Table 8 and corresponding discussion

POST-RAD MEASUREMENT CONDITIONS: Items in Table 4 and corresponding discussion

DATA RECORDING: As in Tables 5, 6, and 7 and corresponding discussion

FINAL RESULTS: Items in Table 9 and corresponding discussion

5.1.12.2 Transfer of characterization data to ERRIC. To make as much radiation response data as possible available to U.S. users, the Defense Nuclear Agency supports a data bank for such data at the Electronic Radiation Response Information Center (ERRIC) operated by the Kaman Sciences Corporation. ERRIC is actively collecting data from other data banks and is very much interested in receiving any new data that is taken. It is strongly recommended here, therefore, that the characterization data which is obtained and documented in the characterization report also be sent to ERRIC. ERRIC is equipped to acquire data from computer disks as well as in printed form. The address and telephone number for ERRIC are:

ERRIC  
Kaman Sciences Corporation  
816 State Street  
P.O. Box 1479  
Santa Barbara, CA 93102-1479  
(805)963-6484

5.2 Calculation of Electrical Parameter End-Point Limits. The previous sections of this report have described how radiation response characterization measurements should be made so they can be used for defining lot acceptance tests that will provide hardness assurance in future procurement. At this point the assumption is made therefore that the characterization results have been obtained and the discussion turns to the procedures by which lot acceptance tests should

be defined. The basic goals here are to select the sample size and to calculate post irradiation test criteria from the characterization data such that future radiation lot acceptance tests performed against these criteria will meet a selected objective. Typically, the selected objective will be a desired lot acceptance probability and confidence level.

It is worth noting that the methods described here are not limited just to radiation hardness assurance but can be used for the more general problem of calculating end-point limits to meet a selected lot acceptance objective. They may be of use, therefore, to any manufacturer of parts who is interested in quantifying the lot acceptance results he can expect as a function of the end-point limit or specification value he selects for a given parameter.

**5.2.1 Lot Acceptance Tests.** Lot acceptance tests are based on testing a sample of parts after they have been irradiated and determining whether the sample of parts passes or fails some specified criterion. If a variables test is being used then the measured mean value and standard deviation of the post-irradiation parameter values will be compared to the specified criteria to determine whether the test was passed or failed. If an attribute test (such as an LTPD test) is being used, then specified RHA end-point-limits (RHEPL) and, possibly, functionality, will be used for determining whether each part, individually, has passed or failed the test. Changes, or "deltas" in a parameter may also be used as a RHEPL.

**5.2.1.1 Attribute lot acceptance tests in Military standard procurement.** Because military standard procurement rely almost exclusively on attribute tests, the discussion here mostly addresses this type of test. It should be recognized, however, that, for the same number of samples tested, radiation lot acceptance tests based on variables measurements will usually give higher quality results. Their principal disadvantages are that they are somewhat more complex and costly and require assumptions about the probability distribution to which the parts belong. Attribute tests such as the lot tolerance percent defective (LTPD) tests used in the MIL STD system have the advantages that they require less documentation of test results, do not require as much training for test personnel, and do not depend strongly on assumptions about the probability distributions to which the tested parts belong. The relative merits of these two types of tests were discussed in some detail in the Introduction.

**5.2.1.2 End point limits for LTPD tests.** FIGURE 4 shows the steps to be taken for calculating end-point limits for LTPD lot acceptance tests. TABLE 11 lists these steps in finer detail as a step-by-step check off procedure.

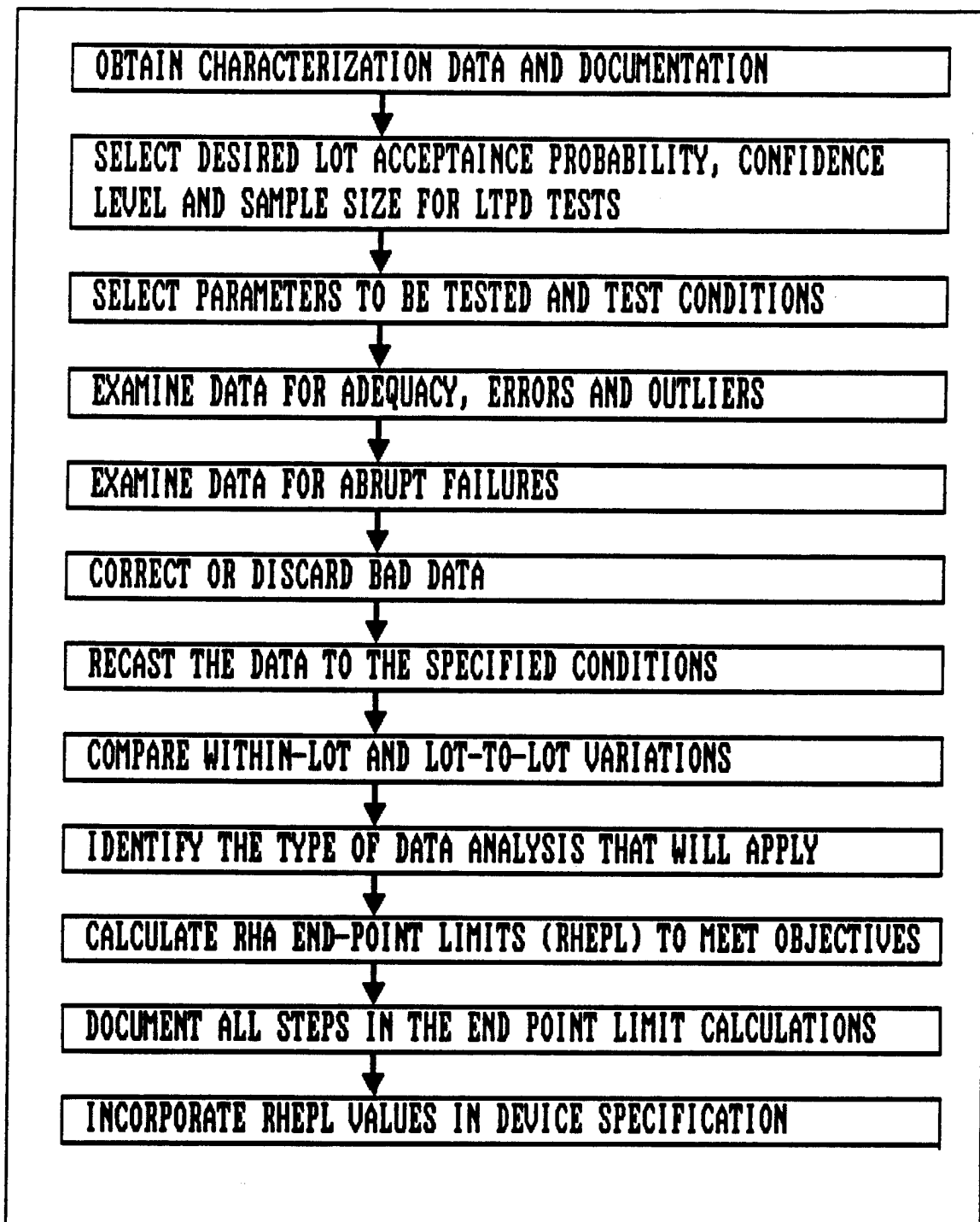


FIGURE 4. Steps for calculating end-point limits for lot acceptance tests.

TABLE 11. Step by step procedure for calculating end-point limits.

<u>Step</u>	<u>Check-Off Item</u>
1.	Select device type and manufacturers
2.	Obtain characterization data and documentation
3.	Select desired lot acceptance probability, confidence level, and sample size for LTPD tests
4.	Select parameters to be tested and test conditions
5.	Begin data examination
6.	Check data for sufficiency
7.	Check for outlying devices
8.	Check for outlying lots
9.	Discard outliers
10.	Check data for abrupt failures
11.	If abrupt failures have a significant likelihood, parameter end point limits usually cannot be calculated
12.	Check for unexpected functional dependencies
13.	Check for systematic or non-random effects
14.	Check for correlations with respect to time of manufacture
15.	Check for unexpected magnitudes of lot-to-lot variations
16.	Check for bad data points
17.	Correct or discard bad data points
18.	Check data for sufficiency
19.	Recast the data to the specified conditions
20.	Determine within-lot and lot-to-lot variations
21.	If within-lot variations are larger than lot-to-lot, use case 1 analysis method to calculate the RHA end-point limits (RHEPL)
22.	If within-lot variations are smaller than lot-to-lot, use case 2 analysis method to calculate the RHEPL.
23.	Incorporate the RHEPL and LTPD lot acceptance test requirements into the device specification.



5.2.1.3 Statistical uncertainties associated with lot acceptance testing. The lot tolerance percent defective tables in MIL-M 38510 and other MIL STD documents are based on statistical formulas for sampling with replacement, i.e. the sample of parts used for the tests is replaced into the lot of parts from which it was drawn. Because radiation tests are damaging, the parts tested are not replaced into the lot. The statistical implications of this fact can be complex and are beyond the scope of this document. In general, statistical uncertainties are reduced when the lot acceptance sample size is large and are further reduced if the lot acceptance history is known. The least desirable situation occurs when only a single lot has been tested and when the sample size is only a few parts, say 4 or less. In this latter case it will be difficult to estimate what the performance characteristics of the passed lot will be. The recommendation is, therefore, that lot acceptance tests based on 4 parts or less should not be used. For small sample sizes, information about the uniformity of the lots is also very important. If a lot were perfectly uniform, for example, then testing a single part would be adequate. If the uniformity of each lot is high then, during the lot acceptance tests, most of the time, either all the parts pass or they all fail. For such uniform lots, a 2/0 or a 4/0 test (presently specified in the group E tests of method 5005 in MIL STD 883) may be able to give some confidence that the passed lots are of high quality. If lots are mostly being rejected because 1 part out of the sample is failing, then the passed lots must be considered to be of low quality.

5.2.2 Definition of RHA End-Point Limits (RHEPL). The parameter values against which the post radiation performance of a part will be compared to determine if the part has passed or failed the test have been termed RHA end-point limits (RHEPL). These RHEPL values are included in the procurement specification and are used for the lot acceptance tests. If the procurement system uses a qualified parts list, as, for example, the present MIL STD system does, then these RHEPL may also be used for part qualification. The discussions which follow explain what decisions must be made before the RHEPL can be calculated and, once the required decisions are made, how they can be calculated from the characterization measurements. If the part can be purchased against any one of several radiation levels, as for example the four ionizing radiation dose levels, M, D, R, and H, shown for MIL STD parts in TABLE 1 (Section 4.2), then a separate RHEPL must be calculated for each radiation level.

A device can cease to function as a result of a radiation exposure and will, obviously, fail the test being conducted. Such failures are not associated with the definition of an end-point limit. Of course, the functional failure of a part will count as a failure for lot acceptance purposes.

5.2.2.1 One and two sided limits. A parameter used for determining whether a device has passed or failed a test, may be bounded by maximum and minimum values, i.e. by "two sided" limits, or by either a maximum or a minimum value, i.e. by a one-sided limit. Because a one-sided limit is the one most commonly used in radiation response testing, only such limits are treated here. The mathematical formulas for the case of two-sided limits are almost identical to the one-sided case so the present discussion can easily be extended to that case

if it is necessary to do so.

### 5.2.3 Criteria for Calculating RHA End-Point Limits (RHEPL).

5.2.3.1 Selection of objectives for lot acceptance tests. Meaningful RHA end-point limits cannot be calculated until the objectives of the lot acceptance testing have been selected. Simply put, if the object of the tests is that at least 90 percent of future lots should pass the test, the end-point limits will be less stringent than if the object is that at least 80 percent of future lots should pass. It should be noted, however, that the statistical uncertainties associated with the relatively small sample sizes that are typically used (tests are usually based on tens of devices but not hundreds) have the consequence that, almost regardless of where the RHEPL is set, there will be a significant probability that a good lot may fail or that a bad lot may pass the specified lot acceptance test. The real constraints on selecting an objective for the LAT and on calculating the corresponding RHEPL, therefore, are the performance of the part and the economic costs of rejecting lots. Thus if the RHEPL is set so that, with 90% confidence, 10% of future lots may be expected to pass, then the performance of the lots that pass may be very good but the costs of rejecting such a high percentage of lots may make the part too expensive to use. Similarly, if the end-point limit is set so that 90% of future lots may be expected to pass, then the cost of the part may be attractive but the performance of the part may not as good as may be desired. The objectives of the lot acceptance tests are thus seen as a trade-off between passing the largest percentage of lots and keeping end-point limits which will make the performance of the part desirable.

5.2.3.2. Lot rejection probability and choice of end points. In the data analysis sections which follow, these guidelines show how lot rejection probability depends on the choice of end-point limits. They should, therefore, assist manufacturers or specification developers in selecting end-point limits which best meet their needs. The discussion also shows that lot to lot variability in radiation response can present serious difficulties to end-point limit selection. For this latter case, which is common, the methods recommended here may provide a better assessment of the risks associated with different values of the end-point limits than other methods which have been used.

5.2.3.3. Many parameters and environments. The most tractable case for calculating end-point limits that are to be used for lot acceptance tests is the case of a single radiation environment and a single device parameter. As soon as two or more different and independent test parameters are involved in lot acceptance, then the probabilities of passing for each parameter have to be higher by amounts such that the product of all the passing probabilities equals the probability of passing that is desired. Thus for example, if two different and independent parameters are specified and the desired lot acceptance probability is 0.9, then the respective passing probabilities,  $P_1$  and  $P_2$ , have to be such that  $(P_1)(P_2) = 0.9$ .

The complexities of the calculations for combined radiation environ-

ments or parameters or both are such as to put them outside the scope of this document. Unless otherwise noted, therefore, the analysis examples given in the sections which follow are for a single radiation environment and a single device parameter.

5.2.3.3.1. Many parameters. In practice, device specifications generally do have to require that post radiation tests be made on several parameters against specified end-point limits. The recommendation here is that, whenever possible, the characterization data be used to select the most sensitive critical parameter and that the end-point limit be calculated for that parameter to give the desired lot acceptance probability. The end-point limits for the other relevant parameters then must be calculated to give sufficiently high passing probabilities so that those parameters will not cause a significant number of lot failures. Methods are presently being developed to deal with the case when two or more independent parameters have comparable likelihoods of causing failure but they are not yet in a form which could be included here.

5.2.3.4 End points and electrical condistions. It is common also for a device specification to give values of a lot acceptance parameter as a function of the operating condition of the device. Thus, for example, end-point-limits may be given for the post irradiation gain of a transistor as a function of the collector current. It can then happen, because the calculations are statistical in nature, that different mean values and standard deviations in the characterization data for the different collector currents can result in calculated end-point-limits that do not behave in the expected way as function of the collector current. The following caution is therefore advised:

Caution: Data deficiencies and/or statistical effects can lead to end-point-limits, calculated as a function of some device parameter, that do not behave in a reasonable way. For example, for a given neutron fluence, the calculated RHEPL for transistor gain may show a decrease with increasing collector current, instead of an increase (in the region below the collector current at which the gain is a maximum). It is important therefore that the calculated results be subjected to a "sanity check" to make sure that "unphysical" end-point-limits are not entered into the device specifications. In general, a RHEPL should be a smooth function of bias and radiation stress. It should be noted in this connection, however, that a gradual approach to failure may not always be monotonic; sometimes, for example, a parameter may first increase with radiation fluence and then subsequently decrease.

5.2.3.5 Abrupt failures. If abrupt failures are expected to be the dominant failure mode at the radiation levels required for the lot acceptance tests, any parameter end-point-limits that are used should be calculated so that they will not cause a significant number of lot failures. This situation resembles that of the several parameters discussed in Section 5.2.3.3. A method for estimating end-point limits for devices which suffer abrupt failure has been given by Namenson and Arimura (1985); this paper is listed in Section 2.2. In

practice, even though lot acceptance tests may be conducted at a radiation level where some abrupt failures may occur, the subject part type should not be used in a system application if the specified radiation level is such that the likelihood of abrupt failure is expected to be significant; a derating factor of two on the radiation level has sometimes been used but a more accurate value should be based on actual fluence to failure data.

5.2.3.6 Use of end-point limits for system design. Strictly speaking, the end-point limits used for lot acceptance tests do not guarantee how the parts will behave in a system exposed to a specified radiation environment. Nevertheless, systems designers frequently use the RHEPL as the starting point for derating a given parameter for a particular system application. For systems with moderate RHA requirements, the derating may be very small or the RHEPL may even be used directly in the system design. For systems with more stringent RHA requirements, the RHEPL value may be derated significantly or may be set so that only the hardest lots are accepted for system production. Thus, if a part specification is being developed for a particular system, the needs of the design engineer should be considered. The entire topic of lot acceptance and its impact on system design and survivability, while very much deserving of detailed discussion, is beyond the scope of this document.

5.2.3.7 An assumed lot acceptance objective. The many factors involved in selecting an objective for the lot acceptance tests have been discussed in section 5.2.3.1. To facilitate the data analysis discussions which follow, the lot acceptance objective is here taken to be that, with 90 percent confidence, at least 90 percent of future lots are intended to pass. This objective means specifically that the end-point-limit, which determines the probability,  $P_s$ , that a single part will pass the test, must be set so that the probability that the entire test will be passed is 90 percent. This particular objective, in general, does not unduly penalize the performance specifications for a device nor does it place undue requirements on the amount or quality of characterization data. The assumption of a specific lot acceptance objective makes it possible to give actual numerical values for the examples which are to be discussed. The formulas required are given in their parametric forms so that calculations can be made for other lot acceptance objectives.

5.2.4 Data Analysis. Because most radiation response results display significant and seemingly random variations, the methods needed to analyze such data are statistical in nature. In addition, most radiation testing involves the use of sample parts which are destroyed by the tests, so the analysis techniques and expectations of future performance (against which lot acceptance parameter end-point limits are calculated) must be based on statistics of sampling without replacement. The sections which follow discuss general analysis principles and their applications but do not attempt to cover all the data analysis variations that can occur in practice.

5.2.4.1 Data examination. A necessary prerequisite for beginning any data analysis, which was mentioned previously but must be discussed in greater detail again because of its crucial importance, is an examination of the data to ensure

that the data do not contain any faulty measurements or non-random effects. The data should be examined also for sufficiency. Data examination is all the more important when a significant amount of time has elapsed between the characterization measurements and the data analysis or when the person or organization undertaking the data analysis is different from the persons who took the data in the first place. Some of the most common reasons for suspecting that data may be bad are discussed below.

5.2.4.1.1 Outlying devices. It is not uncommon, in a batch of measurements, to find that one or more devices out of the sample show failure fluences or post-irradiation parameter values that are significantly outside the values that would be expected from the mean value and variance for the rest of the sample. (Outlying devices may occasionally be found also in the pre-irradiation measurements. The assumption here is that the examination of the pre-irradiation data has eliminated any such devices from the characterization sample.) Although the identification of an "outlier" can sometimes be difficult, a plot of the cumulative probability distribution for the radiation fluences at which the devices fail (or the post-irradiation parameter values) will usually show that the device in question is not part of the population distribution that is characteristic of the rest of the sample. A more detailed discussion of cumulative probability plots may be found in textbooks on statistics or in Appendix E on Statistical Techniques in DNA report 5910 listed in Section 2.1.1. The combined MIL Handbook entitled: "Total Dose and Neutron Hardness Assurance Guidelines for Semiconductor Devices and Microcircuits" also contains an appendix on statistical techniques. A discussion of how to identify outliers may be found in ASTM standard E178-75 entitled: "Dealing with Outlying Observations."

5.2.4.1.2 Outlying lots. In this situation, data is available for a number of lots and an examination of the data shows that one or more of the lots are showing an unusual mean value or standard deviation. Again, a cumulative probability plot can be made of the data to evaluate whether the suspect lot or lots belong to a different population of lots.

5.2.4.1.3 Sufficiency of data. The first step in preparation for data analysis is to see if there is sufficient data for deriving end-point limits. The recommendation in these guidelines is that the characterization sample should consist of 3 different lots taken at least one month apart, with 5 wafers per lot and 5 parts per wafer taken one from each quadrant and one from the center. The minimum sample size that is recommended is 5 different lots with 5 samples per lot. The data should also contain a range of values and radiation stresses. Thus, for example, if step-stress measurements were performed and all the parts failed in a single "bin" (where a bin is defined as the interval between one fluence and the next higher fluence), there is not enough data for an analysis. If it happens that there is no way to acquire sufficient data, special analysis techniques may be required and/or some worst case assumptions may be needed to supplement the data. Sometimes it may happen that the number of lots used for obtaining the characterization data is not given in the data. For such cases, a method exists for estimating, from the data itself, what the effective sample size of the device population is and this effective sample size can be introduced

into the end-point-limit calculations (see ref. A. I. Namenson, 1979, in Section 2.2).

5.2.4.1.4 Abrupt failures. The data should be examined to see if abrupt failures are likely at the radiation levels that will be required for the lot acceptance tests. If abrupt failures are expected to be the dominant failure mode at these radiation levels, then the mean value and the standard deviation of the fluences to abrupt failure in the characterization data should be used to estimate the radiation level at which the part can be used safely. The fluences to abrupt failure are then used to check for outlying devices, outlying lots, and the sufficiency of the data.

5.2.4.1.5 Unexpected functional dependencies. If a parameter value does not vary smoothly with either bias conditions or radiation dose, the data may be suspect.

5.2.4.1.6 Systematic or non-random effects. The sampling of lots and parts must be a truly random representation of future lots if valid lot acceptance end-points are to be determined. It pays, therefore, to check whether the data is random in nature. Some typical causes of non-random effects are discussed in the sections which follow.

5.2.4.1.6.1 Correlations with respect to time. Lot-to-lot variations should be checked to see if they correlate with time. Examples of such correlations are an average shift with respect to date of manufacture or simply a smooth variation with respect to the date of manufacture. Usually, a look at the data is sufficient to determine if such an effect is occurring. However, more rigorous techniques, such as time-series correlations, for example, exist which can check whether the data varies smoothly with respect to time or has seasonal variations.

5.2.4.1.6.2 Unexpected magnitudes of lot-to-lot variations. If lot-to-lot variations of either the mean value or the standard deviation are much larger or much smaller than expected, it is cause for concern. If a number of lots are very similar, then it may be that the sampling over lots is not truly random. There may be, for example, a single diffusion lot involved or a single wafer. If the lots were produced under total process control, very small variations may result between lots. Then, if future lots will come from the same process, the characterization data is valid. However, if future lots will not all come from the same process, then the data is not valid.

5.2.4.1.6.3 Other systematic effects. If the data comes from several sources, it can vary systematically, i.e. non-randomly, according to the source of the data. Even in one test facility, there may be a systematic dependence on test cell, operator, dosimetry equipment, etc. If lots come from several plants, there may be a systematic dependence on which plant supplied the parts. This type of effect should not be common; it is mentioned here to make sure that is not entirely overlooked.

5.2.4.1.6.4 Checking for systematic effects. If data is suspect, it can be checked for self consistency by removing all data having a common attribute such as date, test facility, place of manufacture, operator, etc. If there are no systematic effects, such removal should not seriously perturb the computed results. Likewise, when parameter values or stress to failure are ranked, there should be no grouping by attribute except for lot identity. Another possibility that should be checked is that the devices did not receive some previous radiation of another type. Thus, as an example, ionizing radiation dose data can be obtained from a data bank, but the devices listed may, previously, have been exposed to neutrons.

5.2.4.2 Correcting the data. If the data examination shows that there may be bad data points present then they have to be either corrected or discarded before the data analysis can proceed.

5.2.4.2.1 Correcting bad data. Sometimes an isolated missing, outlying or otherwise faulty measurement may be inferred by interpolation if the parameter varies smoothly with radiation stress or bias. Whether or not data should be corrected is often a matter of judgment. The documentation should identify where inferred data was used to replace incorrect or missing data.

5.2.4.2.2 Discarding bad data. Often only a single measurement on a device has to be corrected or discarded. However, if one device has many outlying or other obvious mismeasurements, it may be necessary to eliminate the entire series of measurements on that device and seek an explanation of what went wrong. It may be a case of a mismeasurement or of the measuring equipment itself having an effect on the device. On the other hand, the device itself may be an outlier and the question is then raised as to how many outliers will be likely in practice, i.e. when devices are procured for system development and production. If the data shows evidence of many apparent mismeasurements, outlying devices, or outlying lots, then all of the data comes into question. When data is discarded, such action should be documented.

5.2.4.3 Recasting the data to the specified conditions. The assumption is now made that the data examination has been successfully completed and that the data to be analyzed is satisfactory in all respects. One final task now remains before the actual calculation of the end-point limits can be made and that is that the data must be recast into the conditions that will be specified for the lot acceptance tests. Thus, if the lot acceptance test is to be made on a particular parameter, PAR, at a radiation level PHI(SPEC), then the post radiation values PAR(PHI(SPEC)) must be obtained from the characterization data and they must be obtained for the bias conditions that will also be specified in the procurement document. In general these values will be obtainable by interpolation. In the case of abrupt failure, defined in Section 5.1.8.7 as a failure level which cannot be determined by interpolation, the mean value and standard deviation of the fluences to abrupt failure in the characterization data should be used estimate the radiation level at which the part can be used safely.

5.2.4.4 Examples of data analyses. Depending on the exact nature of the data, the statistical methods that should be used to analyze the data and to calculate the required end-point limits range from relatively simple techniques to some that are still under development. Examples are given below for two cases for which the calculations are relatively straightforward. All statistical quantities are assumed to obey lognormal probability distributions, i.e. the logarithms of the parameter values are normally distributed. This assumption may be considered reasonable because many of the parameters that are of interest for radiation effects in devices have been observed experimentally to obey a lognormal distribution. In any case, extensions of the analysis techniques discussed below can be made to other types of probability distributions.

5.2.4.4.1. Parameters and delta-parameters. For convenience, the analyses are discussed in terms of the value of the parameter in question after irradiation. In practice, however, it is often useful to measure the changes, or deltas, in a parameter value produced by the irradiation. Again, the extension from the formulas given to the case of parameter deltas is straightforward. It should be noted that lot acceptance tests based on parameter deltas can be somewhat more costly because they require that part identity be maintained and that pre and post-irradiation parameter values be recorded. They should not be overlooked, however, because, in some cases, they can provide better hardness assurance than lot acceptance tests based just on the post-irradiation parameter value. The example given for case 1 is based on the values of a parameter; the example given for case 2 shows how deltas may be used.

5.2.4.4.2 Case 1. Within-lot variations larger than lot-to-lot variations. At the present time, case 1 is an unusual result and, when it occurs, may indicate suspect data. Most commonly, lot-to-lot variations are larger than within-lot variations (discussed here as case 2). Case 1 is being discussed first, however, because the formulas used for it are more familiar. In addition, it may turn out to be true in the future, when total quality control procedures have been successfully implemented, that the wafers coming off of a production lot will be quite uniform and that most of the device variations will be associated with variations across the wafer. This case will apply to such product.

5.2.4.4.3 Assumptions for case 1. Specifically, the assumptions made here are that the parameter being measured shows a graceful decrease in value with increasing radiation stress and that the within-lot variations, or standard deviations, are larger than the lot-to-lot variations. A further assumption is that the within-lot variations do not vary greatly from one lot to another. If this latter assumption does not hold, then, to be on the safe side, the data should be analyzed with the method of case 2. If the above assumptions hold, then the group of lots from which the data was obtained can be considered as a single lot and the total number of parts drawn from all the component lots will be the sample size used in the formulas that require sample size. Let this sample size be  $n$ . Now assume, as a convenient example, that the lot acceptance test will require that 11 parts will be irradiated to a radiation level  $\text{PHI}(\text{SPEC})$  and that all parts must pass for the lot to be passed. To satisfy the lot



acceptance objective, stated as an assumption in Section 5.2.3.7, that with 90 percent confidence at least 90 percent of future lots should pass, each part must have a probability of passing, P, such that:

$$(P)^{11} = 0.9$$

This equation is satisfied if  $P = 0.99$ . For obvious reasons, P is often also called the part survivability.

5.2.4.4.4. Statement of problem. Because the characterization sample was purposely taken so as to represent the performance of future lots as accurately as possible, the problem can now be restated as follows: what is the parameter value, RHEPL, such that, with 90 percent confidence, fraction P of future parts have a parameter value greater than RHEPL (for a parameter that decreases as the radiation stress increases) after being irradiated to radiation level PHI(SPEC)? In response to this question RHEPL is given by :

$$RHEPL = \text{MEAN} [ \text{LN}(\text{PAR}(\text{PHI}(\text{SPEC}))) ] - K_{TL}(C, P, n) * \text{STDEV} [ \text{LN}(\text{PAR}) ],$$

where  $\text{MEAN}[\text{LN}(\text{PAR}(\text{PHI}(\text{SPEC})))]$  is the mean value of the logarithms of the parameter values measured after irradiation to PHI(SPEC) for each of the n devices,  $\text{STDEV}(\text{LN}(\text{PAR}))$  is the standard deviation of these same logarithms, and  $K_{TL}(C, P, n)$  is the one sided tolerance limit factor for confidence C, part survivability P, and sample size n. Note that a minus sign is used in the equation for a parameter which decreases in value as the radiation stress increases and a plus sign is used for a parameter that increases in value as the radiation stress increases. The one sided tolerance limit factors may be found in tables in the statistical references previously cited. Some of the most commonly used values are given in TABLE 12.

The equation for the mean value of the logarithms is:

$$\text{MEAN} [ \text{LN} (\text{PAR}(\text{PHI}(\text{SPEC}))) ] = \frac{1}{n} \sum_{i=1}^n \text{LN} (\text{PAR}_i(\text{PHI}(\text{SPEC})))$$

where  $\text{PAR}_i(\text{PHI}(\text{SPEC}))$  denotes the value of the parameter after irradiation to PHI(SPEC) for the ith device. The standard deviation of these logarithms is given by:

$$\text{STDEV} (\text{LN} (\text{PAR})) =$$

$$\left[ \frac{1}{n-1} \sum_{i=1}^n [ \text{LN} (\text{PAR}_i(\text{PHI}(\text{SPEC})) - \text{MEAN} (\text{LN} (\text{PAR}(\text{PHI}(\text{SPEC})))) ]^2 \right]^{1/2}$$

TABLE 12. One sided tolerance limit factors -  $k_{t1}$ .

CONFIDENCE C = 0.90					
	P				
N	0.90	0.95	0.99	0.999	0.9999
3	4.259	5.311	7.340	9.651	11.566
4	3.188	3.957	5.438	7.129	8.533
5	2.742	3.400	4.666	6.111	7.311
6	2.493	3.091	4.243	5.555	6.645
7	2.332	2.894	3.972	5.202	6.222
8	2.218	2.755	3.783	4.955	5.927
9	2.133	2.649	3.641	4.771	5.708
10	2.065	2.568	3.532	4.628	5.538
11	2.011	2.503	3.443	4.514	5.402
12	1.966	2.448	3.371	4.420	5.290
13	1.928	2.403	3.309	4.341	5.196
14	1.895	2.363	3.257	4.273	5.116
15	1.867	2.329	3.212	4.215	5.046
16	1.842	2.299	3.172	4.164	4.986
17	1.819	2.272	3.137	4.119	4.932
18	1.800	2.249	3.105	4.078	4.884
19	1.781	2.228	3.077	4.042	4.841
20	1.765	2.208	3.052	4.009	4.802
21	1.750	2.190	3.028	3.979	4.766
22	1.736	2.174	3.006	3.952	4.734
23	1.724	2.159	2.987	3.926	4.704
24	1.712	2.145	2.969	3.903	4.677
25	1.701	2.132	2.952	3.882	4.651
30	1.657	2.080	2.884	3.794	4.546
35	1.623	2.041	2.833	3.729	4.470
40	1.598	2.010	2.793	3.678	4.411
45	1.576	1.986	2.761	3.638	4.363
50	1.559	1.965	2.735	3.605	4.324
60	1.532	1.933	2.694	3.552	4.262
70	1.511	1.909	2.662	3.513	4.215
80	1.494	1.890	2.637	3.482	4.178
90	1.481	1.874	2.617	3.456	4.148
100	1.470	1.861	2.601	3.435	4.124

5.2.4.4.4.1 An illustrative example of an RHEPL calculation for case 1.  
For this example the following assumptions are made:

- a) Lot acceptance tests will be performed on the current gain of 2N2222 transistors after irradiation to  $\text{PHI}(\text{SPEC}) = 2.5 \times 10^{13}$  neutrons/cm<sup>2</sup> (1MeV silicon displacement damage equivalent). The collector current, bias voltages, and temperature for the test will be given in the device specification.
- b) An 11/0 LAT test will be used, i.e. 11 devices will be irradiated to  $2.5 \times 10^{13}$  neutrons/cm<sup>2</sup> and, if even 1 device fails, the lot will not be accepted. (In MIL STD practice, if one part out of the first 11 fails, then a drawing of 7 additional devices is allowed and the lot passes if there are no further failures; this extension of the LTPD test will not be treated here.)
- c) With 90 percent confidence (i.e.  $C = 0.90$ ), at least 90 percent of the lots should pass; this assumption was made in Section 5.2.3.7 precisely so that examples such as this one could be calculated. This assumption together with assumption b) means that  $P$  must be 0.99.
- d) The characterization data was adequate to provide post-irradiation current gain values, at the required collector current, bias voltage, and temperature at  $2.5 \times 10^{13}$  neutrons/cm<sup>2</sup>. This data is shown in TABLE 13. Because this is an illustrative example, data is shown for only 10 devices. In actual practice, a sample size of 10 should not be considered adequate to support the calculation of an end-point limit.

For the values in TABLE 13, the following quantities may be calculated:

$$\text{MEAN}(\text{LN}(h_{FE}(\text{PHI}(\text{SPEC})))) = 4.591 \text{ and}$$

$$\text{STDEV}(\text{LN}(h_{FE}(\text{PHI}(\text{SPEC})))) = 0.107.$$

Assumptions b) and c) make  $C = 0.90$  and  $P = 0.99$ . The size of the characterization sample is 10. For  $C = 0.90$ ,  $P = 0.99$ , and  $n = 10$ , the one sided tolerance limit factor,  $K_{TL}$ , is found in TABLE 12 to be 3.532. The end-point limit, RHEPL, is thus:

$$\text{RHEPL} = 4.591 - 3.532 * 0.107 = 4.213$$

In more familiar terms, the geometric mean value of the current gain for the ten devices in TABLE 12 is 98.6, the plus and minus one standard deviation gains are 109.7 and 88.6 respectively, and the end-point limit for the gain is 67.6 ( $= \exp(4.213)$ ). Lot acceptance tests for 2N2222 transistors would then be performed in the future by irradiating 11 devices from each lot to  $2.5 \times 10^{13}$  neutrons per cm<sup>2</sup> and requiring that each device out of the 11 have a post irradiation gain greater than 67.6; otherwise the lot is rejected.

TABLE 13. Post-irradiation data for ten 2n2222 transistors.

PHI(SPEC) = $2.5 \times 10^{13}$ neutrons/cm <sup>2</sup> (1 MeV Si damage equivalent)		
DEVICE NUMBER	$h_{FE}(PHI(SPEC))$	$\ln(h_{FE}(PHI(SPEC)))$
1	108.8	4.689
2	105.4	4.657
3	93.7	4.540
4	97.7	4.582
5	102.6	4.630
6	104.5	4.650
7	84.1	4.431
8	101.1	4.616
9	112.5	4.723
10	81.1	4.396

5.2.4.4.5 Case 2. Lot-to-lot variations larger than within lot variations. Case 2 is applicable when within-lot standard deviations are small compared to lot-to-lot variations. In this case, the effective sample size for the RHEPL calculations is the number of lots and not the number of devices used for the characterization measurements. An approximate analysis method for this case was developed by I. Arimura and A. Namenson and published in IEEE Trans. Nucl. Sci., NS-30, 4322, December 1983. The method assumes that the parameters follow a normal or lognormal probability distribution but it can be modified for a different distribution if necessary. Once again the assumption described in Section 5.2.3.7 is made, namely that the object of the lot acceptance tests is, with 90 percent confidence, to have at least 90 percent of lots pass. It is assumed also that an 11/0 LTPD test will be used for lot acceptance. This last assumption means that, again, the individual part survival probability of the lot being tested for acceptance must be  $P = .99$ .

5.2.4.4.5.1 Sampling for multi-lot analysis. Ideally, there should be at least 5 lots with at least 5 parts in each lot. If the within-lot variations are very small compared to the lot-to-lot variations, the requirement on having at least 5 parts per lot may be waived.

5.2.4.4.5.2 Steps in multi-lot analysis. The following steps are then used in the calculation:

- A. Let the number of lots be  $N$  and the number of devices in each lot be  $n_i$ . For the  $i$ th lot, calculate the mean value and the standard deviation of

the given parameter. Specifically, for the Ith, lot the quantities calculated are  $MEAN_I(PAR(RAD))$  and  $STDEV_I(PAR(RAD))$  as given by the following equations:

$$MEAN_I [PAR (RAD)] = \frac{1}{n_I} \sum_{j=1}^{n_I} PAR_{Ij} (RAD)$$

where  $PAR_{Ij}(RAD)$  is the measured value of  $PAR(RAD)$  for the jth device in the Ith lot, and

$$STDEV [PAR (RAD)] =$$

$$\left[ \frac{1}{n_I - 1} \sum_{j=1}^{n_I} [PAR_{Ij} (RAD) - MEAN_I PAR (RAD)]^2 \right]^{1/2}$$

- B. For each lot multiply the standard deviation by 2.326 (see explanation below) and add it to the mean (addition is used for a parameter that increases in value with increasing radiation level). This gives a limit:

$$LIM_I = MEAN_I(PAR(RAD)) + 2.326 * STDEV_I(PAR(RAD)) \quad \text{for the Ith lot.}$$

- C. For the N values of  $LIM_I$ , obtain the  $MEAN(LIM)$  and the standard deviation  $STDEV(LIM)$ .

- D. Look up the one-sided-tolerance-limit factor  $K_{TL}$  for 90% probability and 90% confidence and for a sample size corresponding to N, the number of lots.

- E. Use the following equation to obtain the desired RHEPL:

$$RHEPL = MEAN(LIM) + K_{TL}(C = .9, P = .9, N) * STDEV(LIM)$$

5.2.4.4.5.3 The rationale of the method given above is to examine the distribution of the 99 percentile points of the different lots and treat them as a normal (or lognormal) distribution. For each lot, adding  $MEAN(PAR) + 2.326 * STDEV(PAR)$  gives the best estimate of the 99 percentile point because, for a standard normal distribution, 2.326 standard deviations above the mean includes 99% of the distribution. The  $K_{TL}$  factor in step D above then is used to obtain an estimate that, with 90% confidence, 90% of the lots will have 99% of their parts within the calculated RHEPL.

5.2.4.4.5.4 An illustrative example of an RHEPL calculation for case 2. The following example was taken from actual data on voltage shifts (deltas) measured after an ionizing radiation dose of 400 KRAD. (This data is interesting for other reasons as well and, for those reasons, will be discussed in greater

detail in APPENDIX II.) The lots do not all have 5 parts per lot, but the within-lot standard deviations are so small compared to the lot-to-lot variations that the case 2 method can still be used. The data in this example is treated as a normal distribution (instead of a lognormal distribution).

The values shown in TABLE 14 yield the values shown in TABLE 15.

TABLE 14. Post-irradiation voltage shifts (deltas).

PHI(SPEC) - 400 KRADS		
LOT NUMBER	DEVICE NUMBER	VOLTAGE SHIFT (mV)
1	1	-6.79
1	2	-6.52
2	1	-5.46
2	2	-5.38
3	1	-3.76
3	2	-3.67
3	3	-3.63
4	1	-2.41
4	2	-2.18
4	3	-1.72
5	1	3.25
5	2	3.60
5	3	3.81
5	4	4.10
5	5	4.23
5	6	4.62
6	1	7.26
6	2	7.28
6	3	7.38
6	4	7.44

TABLE 15. Calculated values for each of the 6 lots given in table 14.

LOT NUMBER	MEAN <sub>I</sub> (PAR(RAD))	STDEV <sub>I</sub> (PAR(RAD))	LIM <sub>I</sub>
1	-6.655	0.1909	-6.211
2	-5.42	0.0566	-5.288
3	-3.687	0.0666	-3.532
4	-2.103	0.3513	-1.286
5	3.935	0.4859	5.065
6	7.34	0.0848	7.537

The values of LIM<sub>I</sub> in TABLE 15 yield following values:

$$\text{MEAN}(\text{LIM}) = -0.6192$$

$$\text{STDEV}(\text{LIM}) = 5.6715.$$

Now for  $C = 0.9$ ,  $P = 0.9$ , and  $N = 6$ ,  $K_{TL}$  is 2.493. The value for the RHEPL therefore is:

$$\text{RHEPL} = -0.6192 + 2.493 * 5.6715 = 13.520.$$

Future lot acceptance tests should therefore be performed against a voltage shift of 13.520 mV.

#### ACKNOWLEDGEMENTS

The authors gratefully acknowledge the sponsorship of the Defense Nuclear Agency's Hardness Assurance Program for the original work on this document and the SPAWAR program for the most recent additions and modifications. For their interest, support, and valuable comments, we particularly wish to thank LCDR Lewis Cohn and Capt. Claude Fore (Defense Nuclear Agency), Dr. Harvey Eisen (Army Research Laboratory), Mr. John Adolphsen (NASA Goddard Space Flight Center), Messrs. William Alfonte and Manfred Espig (Kaman Sciences Corp.), Dr. Itsu Arimura (Boeing Corp.), Drs. Dennis Brown and Edward Petersen (Naval Research Laboratory), Dr. Paltiel Buchman (Aerospace Corp.), Mrs. Mary Anne Dooley (TRW), Mr. James Ferry (AF Phillips Laboratory), Dr. Daniel Fleetwood (Sandia National Laboratories), Mr. Michael Gauthier (ICS Radiation Technologies, Inc.), Mr. Michael Maher (National Semiconductor Corp.), Dr. George Messenger (Messenger Associates), Mr. James Nicklaus (Defense Electronic Support Center), and Mr. Joseph Tirado (Harris Corp.) We also wish to acknowledge valuable suggestions on overstress testing from Mr. James Ritter and Dr. Arthur Campbell (Naval Research Laboratory.)



## APPENDIX I

### A LISTING OF CORRESPONDING ERRIC AND MIL-STD SYMBOLS

#### 10 SCOPE

This appendix is to establish a correlation between ERRIC symbols and MIL-STD symbols. This appendix is not a mandatory part of the handbook. The information contained herein is intended for guidance only.

#### 20 APPLICABLE DOCUMENTS.

This section is not applicable to this appendix.

### 30 A LISTING OF CORRESPONDING ERRIC AND MIL-STD SYMBOLS

ITEM	ERRIC SYMBOL	MIL-STD SYMBOL
<u>CURRENTS</u>		
HIGH LEVEL INPUT CURRENT	IIH	I <sub>IH</sub>
LOW LEVEL INPUT CURRENT	IIL	I <sub>IL</sub>
OUTPUT SHORT CIRCUIT CURRENT	IOS	I <sub>OS</sub>
HIGH LEVEL SUPPLY CURRENT	ICC	I <sub>CCH</sub>
LOW LEVEL SUPPLY CURRENT	ICC	I <sub>CCL</sub>
EMITTER-BASE CUTOFF CURRENT	IEBO	I <sub>EBO</sub>
COLLECTOR-BASE CUTOFF CURRENT	ICBO	I <sub>CBO</sub>
CURRENT FLOW INTO AN INPUT TERMINAL	IIN	I <sub>IN</sub>
INPUT OFFSET CURRENT	OFSTI	I <sub>IO</sub>
INPUT BIAS CURRENT	IBIAS	I <sub>IB</sub>
ZERO SCALE CURRENT	IZS	I <sub>ZS</sub>
FULL SCALE CURRENT	IFS	I <sub>FS</sub>

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ITEM	ERRIC SYMBOL	MIL-STD SYMBOL
<u>IMPEDANCES</u>		
RESISTANCE	R	R
INPUT RESISTANCE	RI	
OUTPUT IMPEDANCE	ZOUT	Z <sub>o</sub>
OUTPUT RESISTANCE	ROUT	
ON RESISTANCE	RON	
ON RESISTANCE	RDS	R <sub>DS</sub>
<u>TIME</u>		
HIGH-LOW PROPAGATION DELAY TIME	TPHL	t <sub>PHL</sub>
LOW-HIGH PROPAGATION DELAY TIME	TPLH	t <sub>PLH</sub>
REVERSE RECOVERY TIME	TRR	t <sub>RR</sub>
RISE TIME	TR	t <sub>TLH</sub>
FALL TIME	TF	t <sub>THL</sub>
<u>REJECTION RATIOS</u>		
COMMON MODE REJECTION RATIO	CM RR	CM <sub>RR</sub>
POSITIVE POWER SUPPLY REJECTION RATIO	PWSRRP	+PSRR PS <sub>rr</sub>
NEGATIVE POWER SUPPLY REJECTION RATIO	PWSRRN	-PSRR PS <sub>rr</sub>

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ITEM	ERRIC SYMBOL	MIL-STD SYMBOL
<u>GAINS AND TRANSFER RATIOS</u>		
FORWARD CURRENT TRANSFER RATIO	HFE	$h_{FE}$
POWER GAIN	AP	$P_G$
MAXIMUM AUTOMATIC GAIN CONTROL RANGE	MAGC	$A_{GC}$
<u>OTHER</u>		
NOISE FIGURE	NF	$N_F$
SLEW RATE	SL RA	$S_R$
NONLINEARITY	NL	$N_L$
POWER SUPPLY SENSITIVITY	PSSIFS	$P_{SS}I_{FS}$
BIT ERROR	BERR	SIGMA-NL

## APPENDIX II

### EVALUATING DATA WITH CUMULATIVE PROBABILITY PLOTS ON PROBABILITY PAPER

#### 10 SCOPE

This appendix deals with unfortunate but nevertheless frequent problems of suspect data. Part characterization and lot acceptance are not complete without ascertaining the validity of the data. The appendix will concentrate on graphic techniques for evaluating data. While data validation is important, this appendix is not a mandatory part of the handbook. The information contained herein is intended for guidance only.

#### 20 APPLICABLE DOCUMENTS.

This section is not applicable to this appendix. All referenced documents appear in Section 2 of the text.

#### 30 INTRODUCTION

30.1 The importance of checking and validating data cannot be emphasized too strongly. Often, problems of faulty equipment, incorrect assumptions and human error will be known before data analysis begins. After obviously suspect data have been removed, subtle data problems may remain whose resolution will depend on the graphic techniques to be mentioned here. Such problems include deviations from the assumed probability distribution, systematic effects and outliers. Though the methods are applicable to a wide range of situations, this discussion will concentrate on using probability plots to interpret test data.

#### 40 WHAT PROBABILITY PAPER IS AND WHY IT IS USED

40.1 Normal probability paper. FIGURE II-1 illustrates three different ways of depicting a normal distribution. The upper curve is the differential probability function for a normal distribution. The middle curve (the so called "S-curve") is the cumulative normal distribution (the integral of the upper curve) plotted in linear coordinates. The bottom curve is the middle curve with the ordinate distorted so that the S-Curve becomes a straight line. When test data is plotted on this latter scale, the eye can check their fit to an assumed form by checking their fit to a straight line.\* Note that for normal statistics

---

\* But note, however, that the statistics of fitting a straight line to the data does not follow the usual regression analysis. This will become clear when the mechanics and mathematics of making the plots are explained.

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these plots exaggerate the regions of very high and very low probability which are generally the regions of interest.

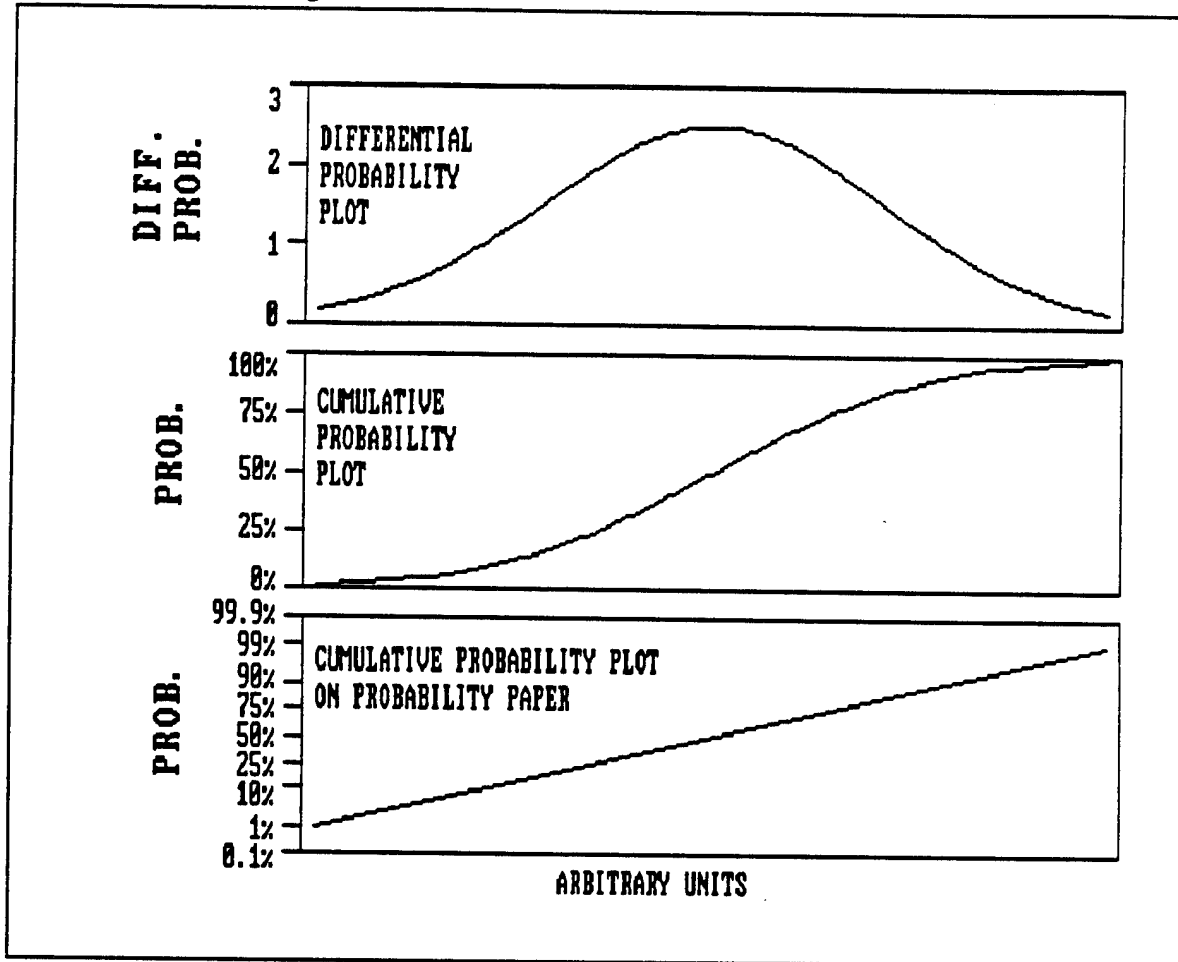


FIGURE II-1. What is probability paper?.

40.2 Different kinds of probability paper exist for different kinds of probability distributions but the discussion here will deal almost exclusively with normal and lognormal statistics. Lognormal probability paper is the same as normal probability paper except that the abscissa is a logarithmic instead of a linear scale.

40.3 Obtaining probability paper. Probability paper may be purchased for most of the commonly applied distributions (e.g. normal, Weibull etc.). Computer made plots, require calculating ordinate positions from functions  $\bar{F}(P)$  where  $P$  is a probability,  $F(Y)$  is a cumulative probability distribution function and  $\bar{F}(P)$

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is its anti-function. (That is  $\bar{F}[F(Y)] = Y$ .) Often a look-up table with interpolation will be sufficient to generate such a function. For the normal distribution, many texts tabulate  $\bar{F}(P)$  as  $Z_p$ .

### 50 MAKING PROBABILITY PLOTS FROM TEST DATA

50.1 The Basic Plot. The construction of plots on probability paper will be explained by example. TABLE II-1 shows 20 simulated data points drawn from

TABLE II-1. Ranking data & preparing for plot on normal probability paper.

Unranked Data		Ranked Data		Rank	P =	
<u>Data</u>	<u>Attribute</u>	<u>Data</u>	<u>Attribute</u>	<u>(i)</u>	<u>i/(N+1)</u>	<u>FBAR(P)</u>
0.2372	ATTRIB. 00	-2.5370	ATTRIB. 03	1	0.0476	-1.6684
-1.3551	ATTRIB. 01	-1.6817	ATTRIB. 07	2	0.0952	-1.3092
-0.6667	ATTRIB. 02	-1.3551	ATTRIB. 01	3	0.1429	-1.0676
-2.5370	ATTRIB. 03	-0.9622	ATTRIB. 10	4	0.1905	-0.8761
-0.1477	ATTRIB. 04	-0.8430	ATTRIB. 16	5	0.2381	-0.7124
0.6332	ATTRIB. 05	-0.6667	ATTRIB. 02	6	0.2857	-0.5659
2.0648	ATTRIB. 06	-0.5864	ATTRIB. 17	7	0.3333	-0.4307
-1.6817	ATTRIB. 07	-0.4012	ATTRIB. 13	8	0.3810	-0.3030
1.2512	ATTRIB. 08	-0.1477	ATTRIB. 04	8	0.4286	-0.1800
1.2845	ATTRIB. 09	0.1326	ATTRIB. 12	9	0.4762	-0.0597
-0.9622	ATTRIB. 10	0.2371	ATTRIB. 00	11	0.5238	0.0597
0.5161	ATTRIB. 11	0.3928	ATTRIB. 18	12	0.5714	0.1800
0.1326	ATTRIB. 12	0.5161	ATTRIB. 11	13	0.6190	0.3030
-0.4012	ATTRIB. 13	0.6332	ATTRIB. 05	14	0.6667	0.4307
0.9639	ATTRIB. 14	0.9639	ATTRIB. 14	15	0.7143	0.5659
1.8462	ATTRIB. 15	1.1946	ATTRIB. 19	16	0.7619	0.7124
-0.8430	ATTRIB. 16	1.2512	ATTRIB. 08	17	0.8095	0.8761
-0.5864	ATTRIB. 17	1.2845	ATTRIB. 09	18	0.8571	1.0676
0.3928	ATTRIB. 18	1.8462	ATTRIB. 15	19	0.9048	1.3092
1.1946	ATTRIB. 19	2.0648	ATTRIB. 06	20	0.9524	1.6684

a normal distribution (col. 1) together with their attributes (col. 2). In this case the attribute is the string "ATTRIB. " followed by the sequence of the point (Nos. 00 through 19). Columns 3 and 4 of the table are the points rearranged by rank with their attributes preserved. Column 5 is the rank,  $i$ , of the ordered points and Column 6 is the probability  $P = i/(N+1)$  where  $N$  is the sample size.

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(In this case  $N=20$ .) For computer made plots, column 7 gives the function  $\bar{F}(P)$  for a normal distribution. FIGURE II-2 shows the resulting graph. Note the fit to a straight line.

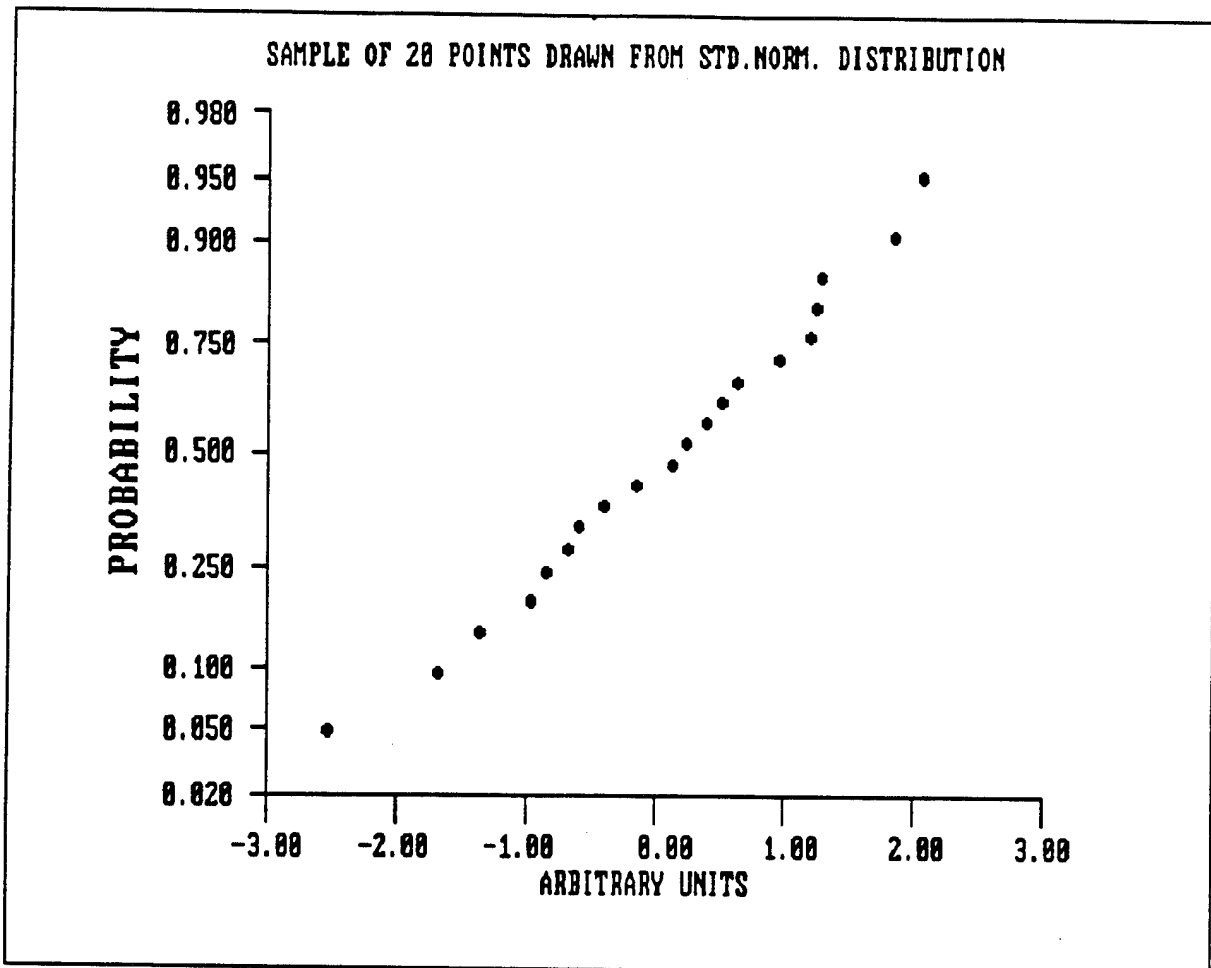


FIGURE II-2. Sample normal probability plot of 20 points - simulated data.

50.2 "Coloring" The Points. The points may be portrayed with different colors and designs according to their attributes so that any systematic effects in the data would become apparent. FIGURE II-3 shows the plot of FIGURE II-2 with the points colored according to whether their first digit is zero or one. Clearly the sequence of the point has nothing to do with its rank.

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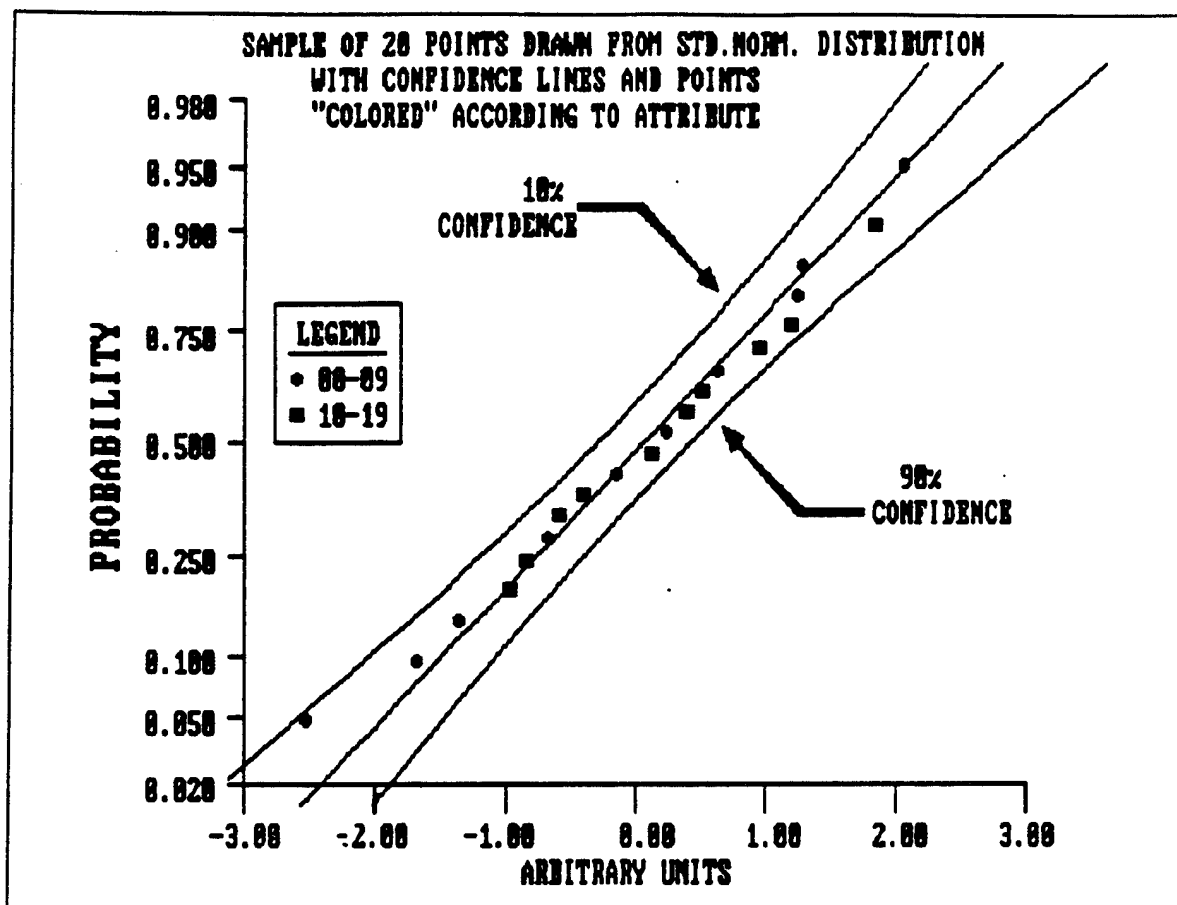


FIGURE II-3. Plot of figure II-2 with coloring and confidence lines.

**50.3 One-Sided Tolerance Limits.** One-sided tolerance lines may be drawn on the plot so that confidence limits may be read directly from the graph. In FIGURE II-3 the confidence lines use an approximation given by Natrella (referenced in Section 2.1.2 of the text). If  $S$  and  $M$  are respective best estimates of the s.d. and mean, the 50% confidence line is very nearly a straight line with slope  $1/S$  and intercept  $M$  with the horizontal 50% probability line.

**50.4 Step-Stress Measurements.** In some cases the values will be accompanied by experimental uncertainty. A typical kind of uncertainty results from step-stress measurements where a parameter or stress-to-failure has merely been determined to be between upper and lower bounds defining a "bin." In such cases, it is advisable to plot the center the bin and display the uncertainty as a horizontal line whose full width is the bin size. A graph of this kind gives a quick check of how the measurement uncertainties compare with the s.d. of the distribution. If these uncertainties are comparable to the s.d., then step-stress analysis may be necessary. For normal distributions, plus and minus



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infinity are valid bounds for a step stress measurement (e.g. a device which survived a maximum test level) and plotting such bounds requires some creativity. A suggestion is to display the finite (lower or upper bound) and use an arrow pointing to plus or minus infinity. Section 60.3.2.1 of this appendix has a figure showing a step-stress probability plot.

50.5 Step-Stress Measurements And Staircase Plots. In some cases - particularly in determining stress to failure using a step-stress measurement - more than one part may fail within a given "bin". If the  $i$ th through  $j$ th parts all failed within the same bin, then probabilities  $i/(N+1)$  through  $j/(N+1)$  should be plotted all with the same center and same "error bar".

50.6 Summary. In summary, the procedure for making probability plots is:

1. Rank the points preserving their attributes
2. Compute probabilities  $i/(N+1)$  where  $i$  is the rank and  $N$  the sample size.
3. Plot the probability vs the value on probability paper. For computer made plots this may require computing  $\bar{F}(P)$  to determine the ordinates.
4. Optionally color the points according to attribute to make apparent any systematics in the data.
5. Optionally draw the one-sided tolerance limits.

50.7 Some Fine Points. The quantity  $i/(N+1)$  derives from order statistics. When  $N$  values are drawn from a uniform distribution from 0 to 1 and ranked, the average value of the  $i$ th ranked point is  $i/(N+1)$ . For normal distributions some prefer to use  $(i-0.3)/(N+0.4)$  as a better approximation for the average positions of ranked points. The difference is usually of no significance. There are some cases in the literature where probability is calculated from  $i/N$  but this is an erroneous procedure except in special cases concerning truncated distributions.

## 60 INTERPRETING PLOTS

60.1 Scrutinizing probability plots requires a fair amount of experience since there are many ways in which data can go wrong and many situations where good data may be rejected because of subjective conclusions. This section will attempt to provide some feel for interpreting probability plots. We will display typical plots, strange looking plots, examples of problematic data and an example of a step-stress measurement.

60.2 Interpreting Typical Plots. To obtain typical plots on normal probability paper, simulated data sets consisting of 50 points were generated from a normal distribution. FIGURE II-4 illustrates an ideal case where about 5 points are above the 90% confidence line and about 5 points are below the 10% confidence line. FIGURE II-5 shows a better than usual fit where many of the points come close the confidence lines, but none are above the 90% confidence line and only two are below the 10% confidence line. Such fits are not unusual. However, if the data fit a straight line too well and none of the measurements come close to the 90% and 10% confidence lines then non-random sampling is

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indicated. FIGURE II-6 is an example of a very bad fit (the worst out of 2000 simulated data sets). Note that points which exceed the confidence bounds tend to group together because the ranking of points assures a correlation between adjacent points. Probability plots are not typical regression plots.

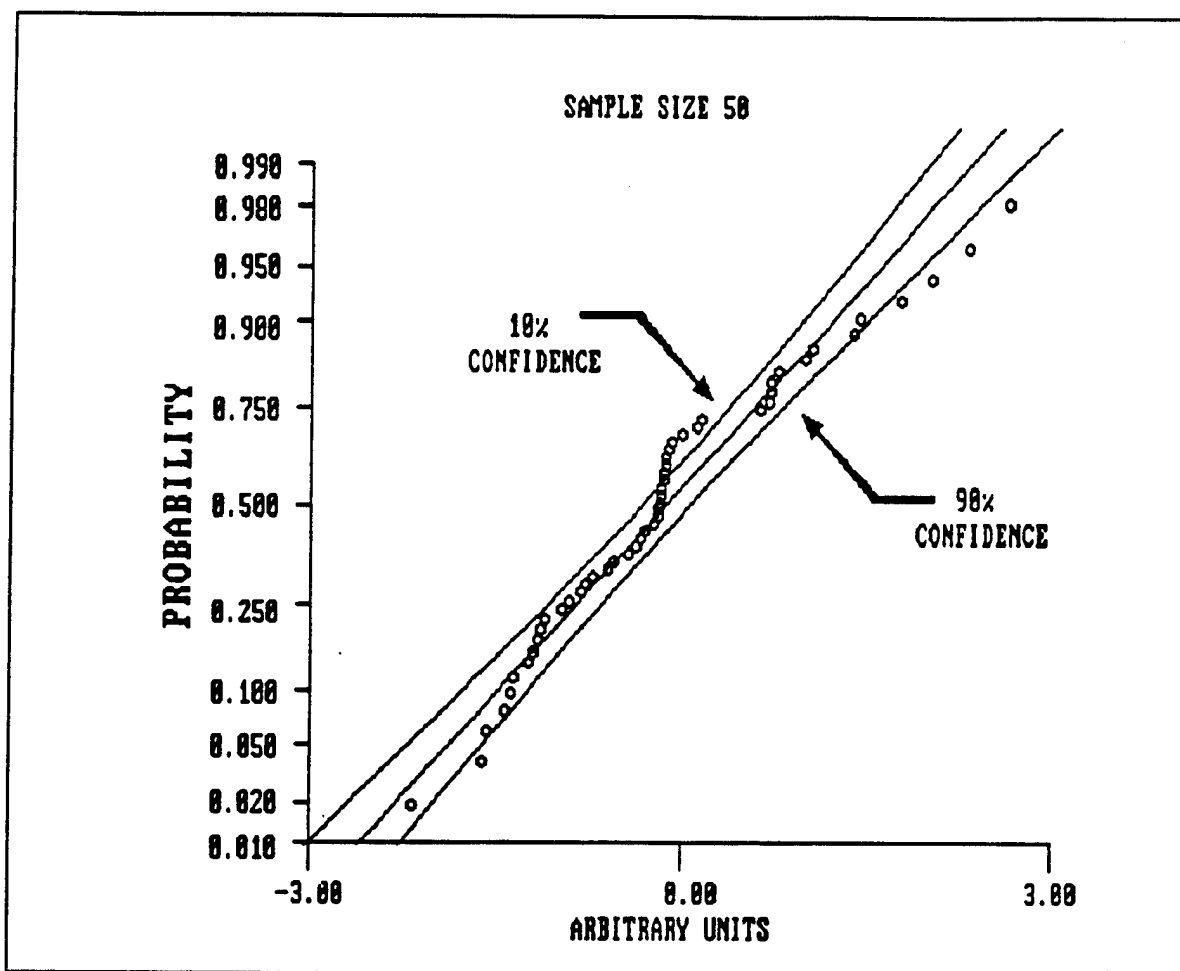


FIGURE II-4. Ideal normal probability plot with 50 points - simulated data.

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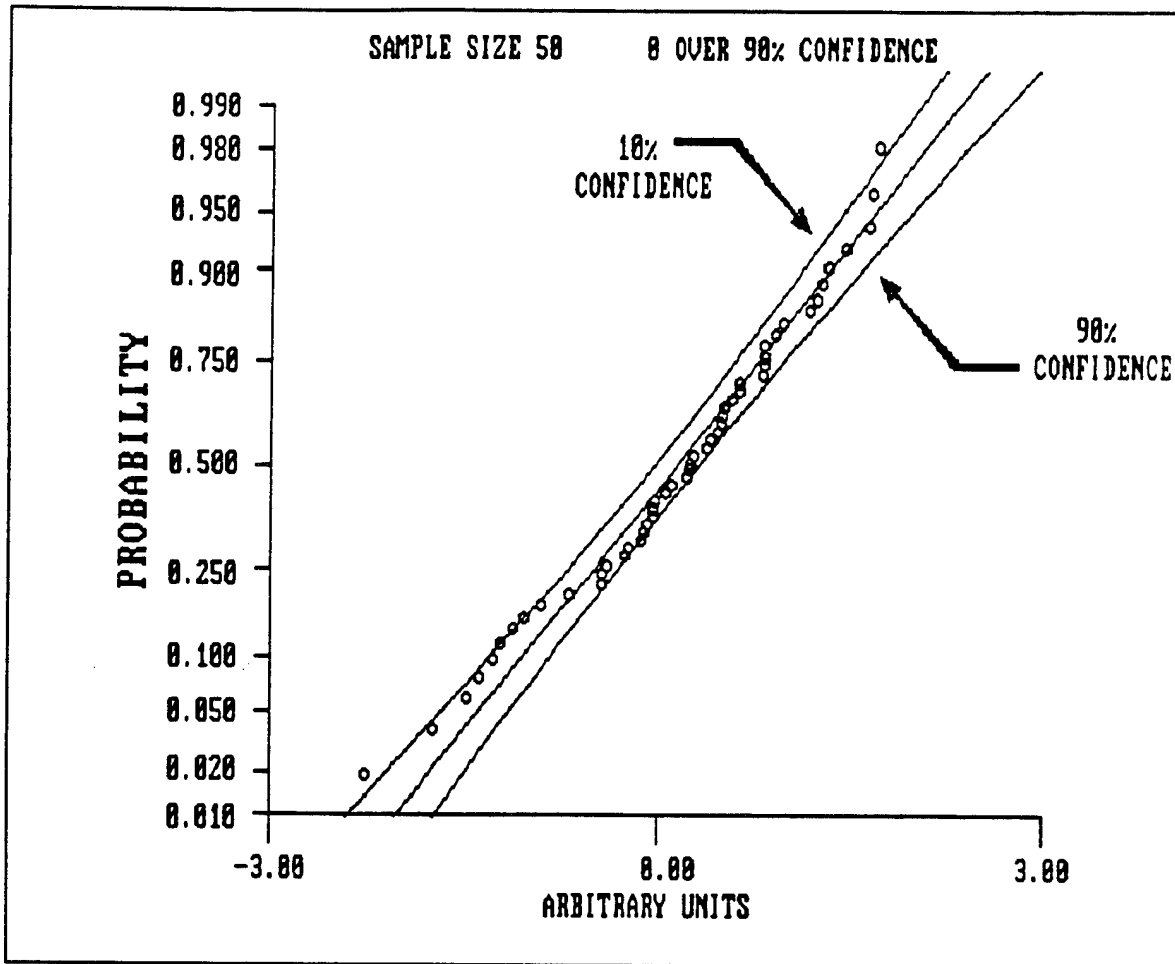


FIGURE II-5. Normal probability plot of 50 points with an overly good but still acceptable - simulated data.

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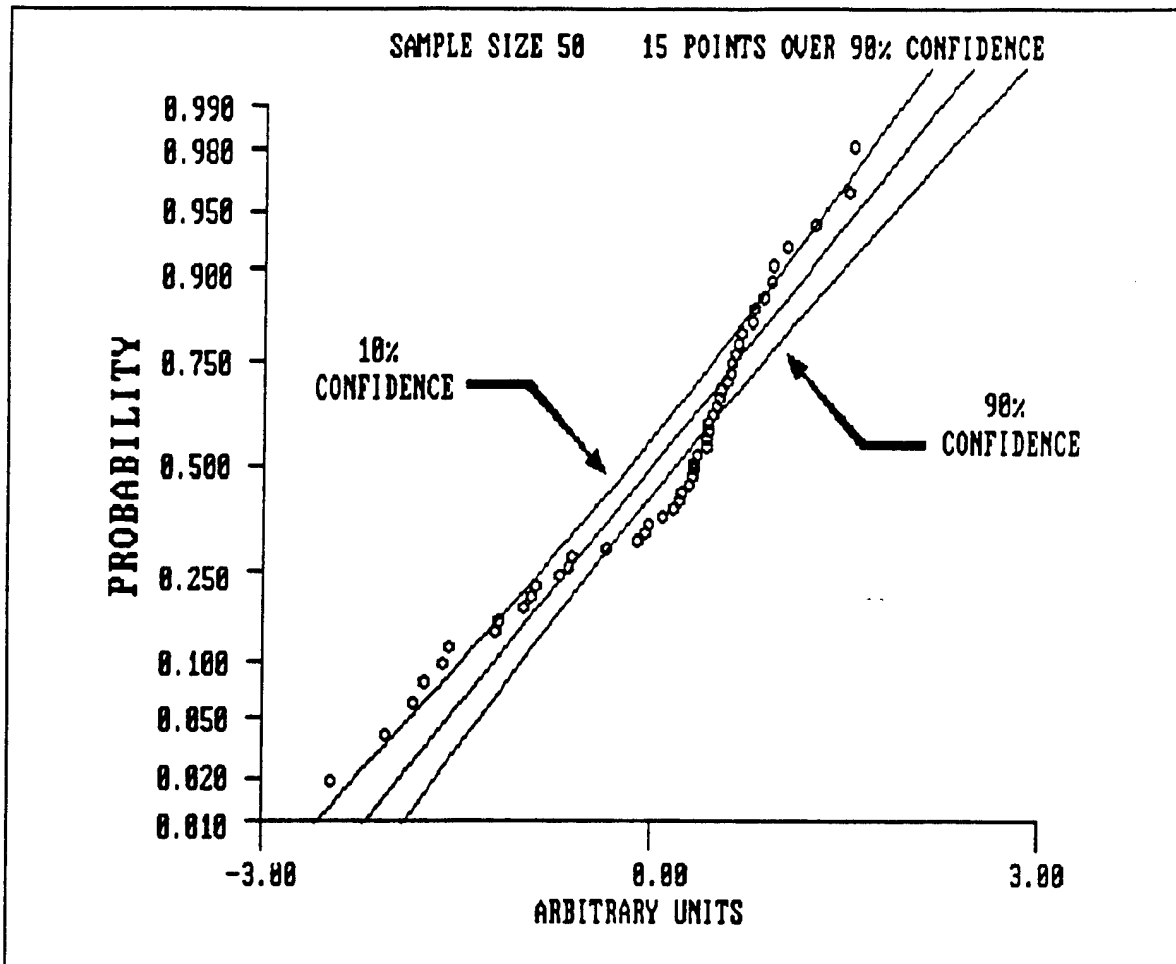


FIGURE II-6. Normal probability plot of 50 points with an exceptionally bad fit - simulated data.

60.2.1 Deviations from A Straight Line. The eye is a fair indicator of when the plot deviates enough from a straight line to suspect that a GOF (Goodness of Fit) test is needed. Even when deviations exist, the assumed distribution may be an acceptable approximation if you restrict yourself to certain probability ranges and/or do "sample size" corrections (discussed later).

60.3 Actual Case Histories and Their Interpretation. To obtain a further feel for problems which will arise in practice, some actual situations are presented and discussed.

60.3.1 Systematic Effects And Inhomogeneous Lots. TABLE II-2 shows a voltage shift for 20 ICs (integrated circuits) irradiated at 400 KRad. There

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were 5 ICs (indicated by attributes R1 through R5) each having 4 nominally identical circuits (indicated by attributes C1 through C4).

TABLE II-2. Voltage shift at 400 Krad.

UNRANKED DATA		RANKED DATA	
VALUE	ATTRIBUTE	RANK	VALUE ATTRIBUTE
4.60,	R1C1	1	-5.70, R4C4
4.31,	R1C2	2	-5.17, R2C3
-2.00,	R1C3	3	-4.95, R4C3
-2.13,	R1C4	4	-4.81, R2C4
7.71,	R2C1	5	-2.62, R5C3
7.67,	R2C2	6	-2.13, R1C4
-5.17,	R2C3	7	-2.00, R1C3
-4.81,	R2C4	8	-1.95, R5C4
4.79,	R3C1	9	-1.80, R3C4
3.76,	R3C2	10	-0.98, R3C3
-0.98,	R3C3	11	3.76, R3C2
-1.80,	R3C4	12	4.31, R1C2
7.89,	R4C1	13	4.60, R1C1
7.58,	R4C2	14	4.73, R5C2
-4.95,	R4C3	15	4.79, R3C1
-5.70,	R4C4	16	5.08, R5C1
5.08,	R5C1	17	7.58, R4C2
4.73,	R5C2	18	7.67, R2C2
-2.62,	R5C3	19	7.71, R2C1
-1.95,	R5C4	20	7.89, R4C1

60.3.1.1 Example of inhomogeneous data. FIGURE II-7 shows the resulting cumulative probability plot on normal probability paper with the 90% and 10% confidence lines. It is clearly not a typical normal distribution. A goodness of fit test (to be discussed later) indicates only a 0.1% confidence that this data could result from a true normal distribution.

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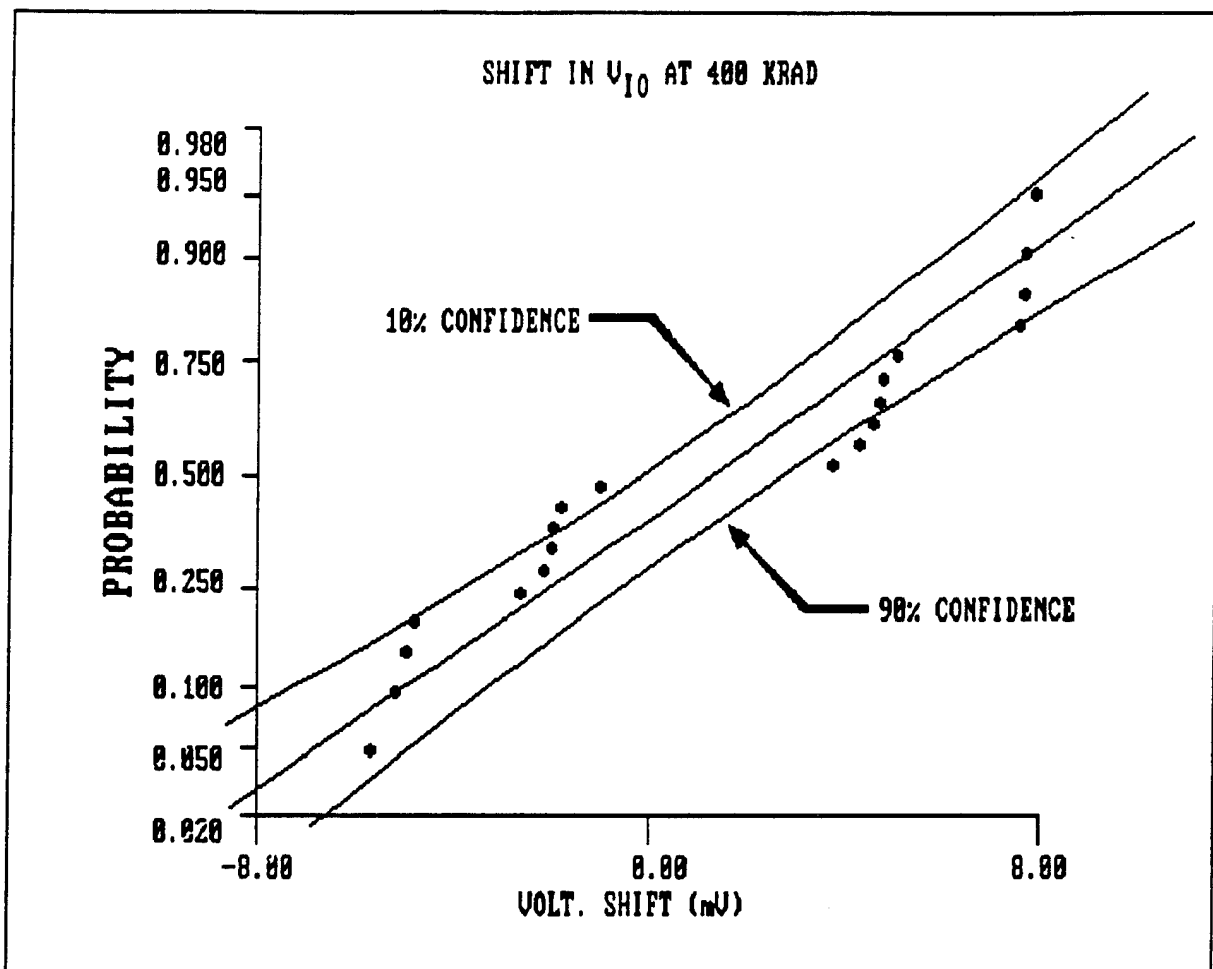


FIGURE II-7. Normal probability plot of actual data that exhibited systematic effects.

60.3.1.1.1 Seeking the causes of inhomogeneity in the example. A study of the plot shows that the ICs must have come from two distinct batches (one batch being ICs R1, R3, R5 and the other being R2, R4). In addition, the response of the circuits varies systematically according to which side of the die the circuit was found (one side being circuits C1 and C2 and the other being C3 and C4). Thus, any circuit belongs to one of 4 groups as illustrated in FIGURE II-8. This figure is the plot of FIGURE II-7 without confidence lines but with the points "colored" to show how each group corresponds to a unique set of attributes. Systematic effects are present, this is an inhomogeneous lot and sample size corrections (Section 70.3 and DNA documents referenced in Section 2.1.1 of the text) indicate an effective sample size of 6 which is not in statistical disagreement with the fact that the data separates into 4 distinct groups. Any

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treatment of this data should use an effective sample size between 4 and 6 and not estimate probabilities greater than about 84%. If the system survivability were to be calculated, the specific buy of parts (how many batches) would be relevant information. Often it is not possible to find a set of attributes which fit some obvious clumping of points. Nevertheless, it would remain very likely that systematics are a serious perturbation and sample size corrections would be appropriate as well as estimates of a maximum reliable survival probability which could be estimated from that effective sample size. A more rigorous calculation than that of MIL-HDBK-280 (See Section 2.1.1 of the text) is not yet available in usable form.

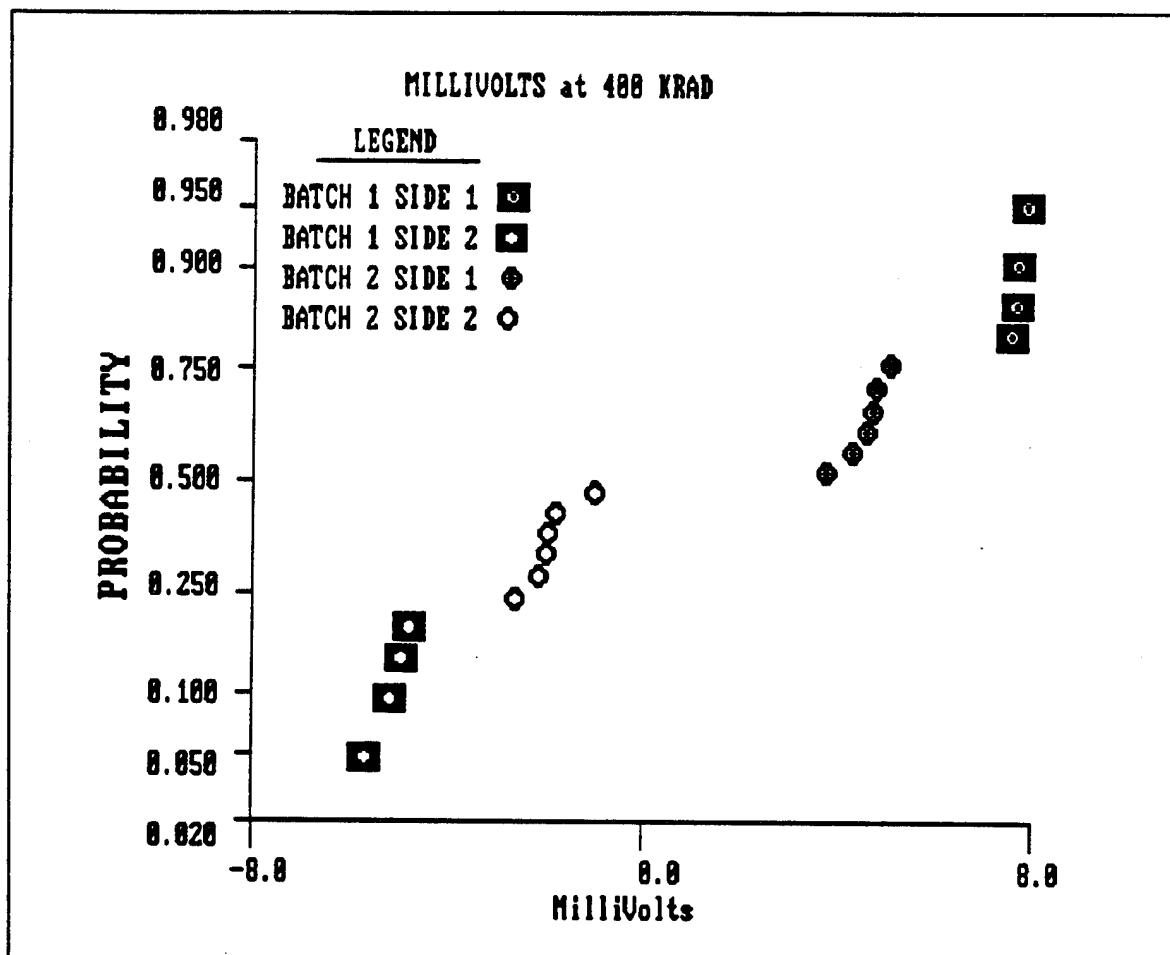


FIGURE II-8. Plot of figure II-7 with confidence lines omitted and points "colored".

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60.3.1.2 Subtle Systematic Effects. We have seen that a typical signature of systematic effects is a grouping of points by attribute with clear gaps between the different groups. In more subtle cases, the groups may not clearly separate and the plot may roughly resemble a straight line. Judgment will be required about the presence of systematics and inhomogeneities.

60.3.2 Possible Outlier and Possible Step-Stress Analysis Required. Probability plots can sometimes be useful in detecting outliers by examining whether the points at the extremes of the plot are reasonably near a straight line fit to the points. The following example will serve the double purpose of illustrating a possible outlier and illustrating a step-stress measurement.

60.3.2.1 Approximate lognormal distribution for this example. The distribution of stress to failure was found from previous experience to be approximately lognormal. Accordingly, the logarithms of the upper and lower bounds corresponding to each step-stress measurement were taken and the stresses to failure were expressed in terms of an average logarithm of stress to failure and a spread in the logarithm between the upper and lower bounds and the logarithms were treated as a step stress measurement for a normal distribution. The points were ranked by their average logarithms. FIGURE II-9, the resulting plot, shows that step-stress analysis (See Namenson 1984, "Statistical Analysis of Step Stress Measurements in Hardness Assurance," referenced in Section 2.2 of the text) might be required.



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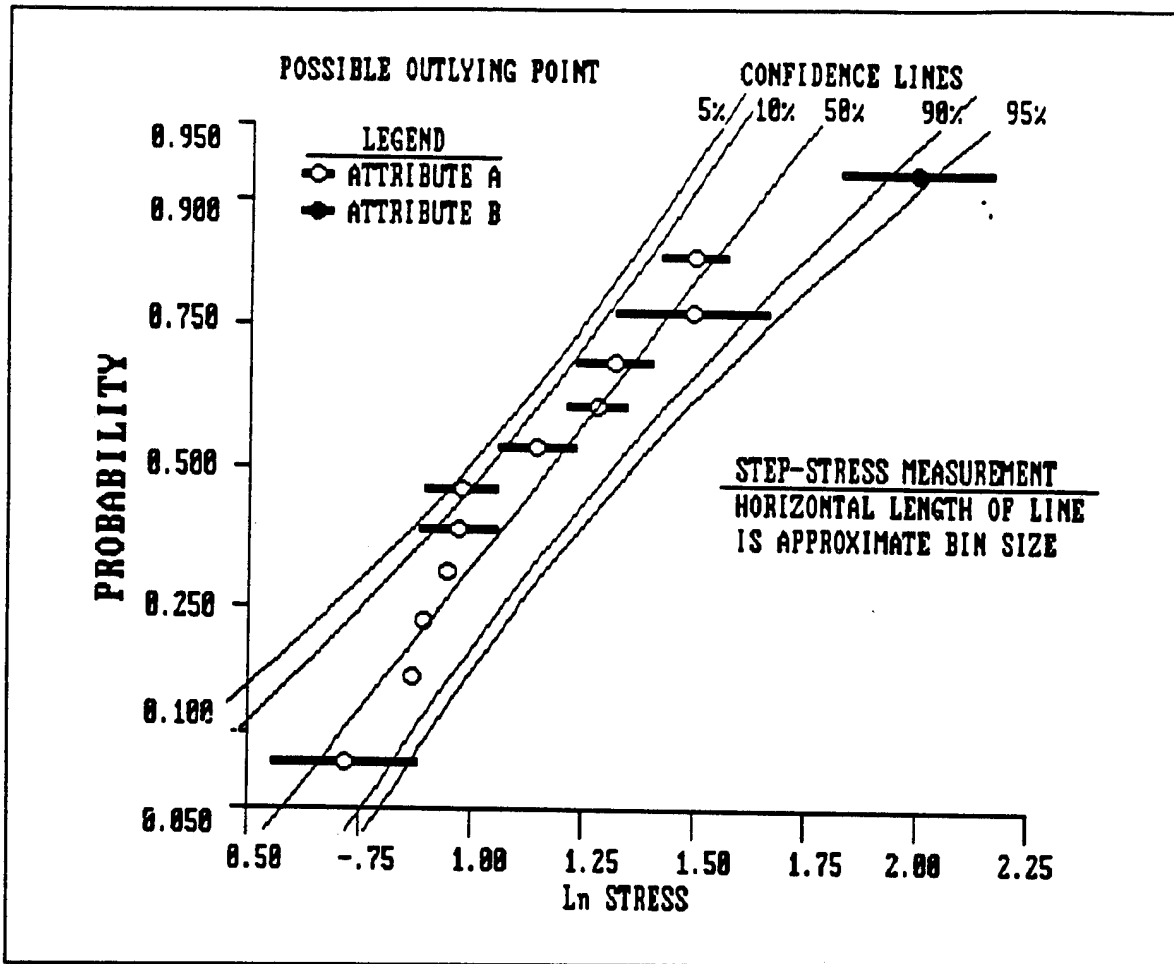


FIGURE II-9. Double example of possible outlier and step-stress data - actual data.

60.3.2.2 Possible outlier in this example. The point corresponding to the highest stress to failure seems too far off the curve (only its lower bound is almost acceptable) hinting that it may be an outlier. Further investigation revealed that in that one case, the stress was applied using a different geometry than for the other cases giving that point an attribute which is not shared by any of the other points. Its distance from the curve and its unique attribute both contribute to a judgmental decision that the point is an outlier.

60.3.3 Lot-to-Lot Variations and Within Lot Variations. Section 5.2.4.4.5 of the main text states that when many lots are involved, the type of analysis which is performed will often depend on the relative magnitudes of the lot-to-lot variations and the within lot variations. In general, this information must be extracted from the data. The example in Section 60.3.1 of this appendix further

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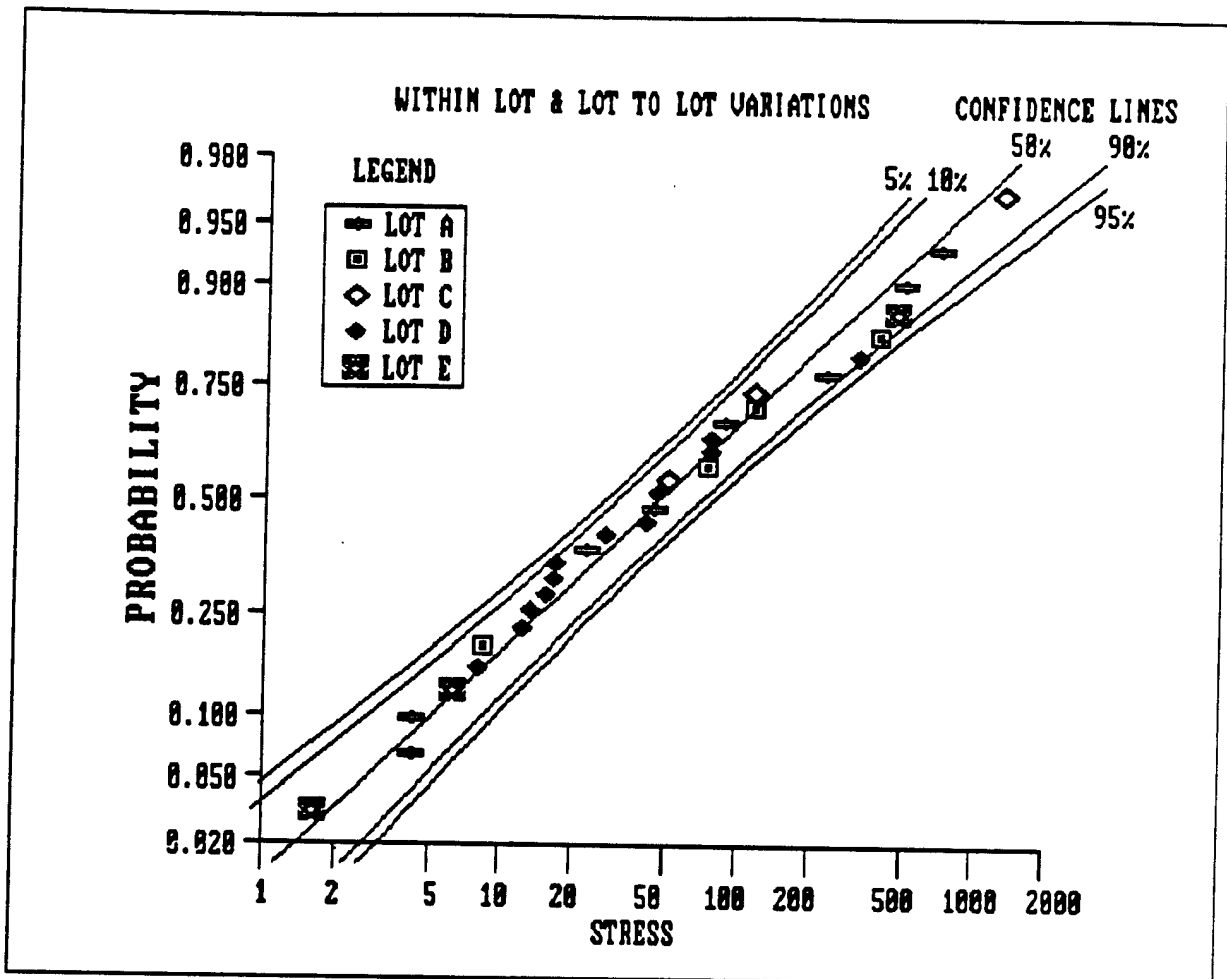


FIGURE II-10. Within-lot variations exceed lot-to-lot variations.

indicates that sometimes a single lot does not reflect a homogeneous population. The lognormal probability plot of FIGURE II-10 shows the opposite case where three different lots were mixed together to produced data which is consistent with a single lot. No doubt, if a large amount of additional data were obtained, systematic lot-to-lot differences would emerge but for the data on hand, a single-lot analysis is adequate with perhaps a sample size correction for added precision and with limitations on the maximum survival probability that can be quoted.

60.3.4 Approximate Distributions. In practice, there is often little or no theory about the probability distribution governing part parameters and stress to failure. Analysis usually proceeds on the basis sometimes limited experience. It is, therefore, prudent not to extrapolate to very high probabilities on the basis of a small amount of data. FIGURE II-11, which will be explained more

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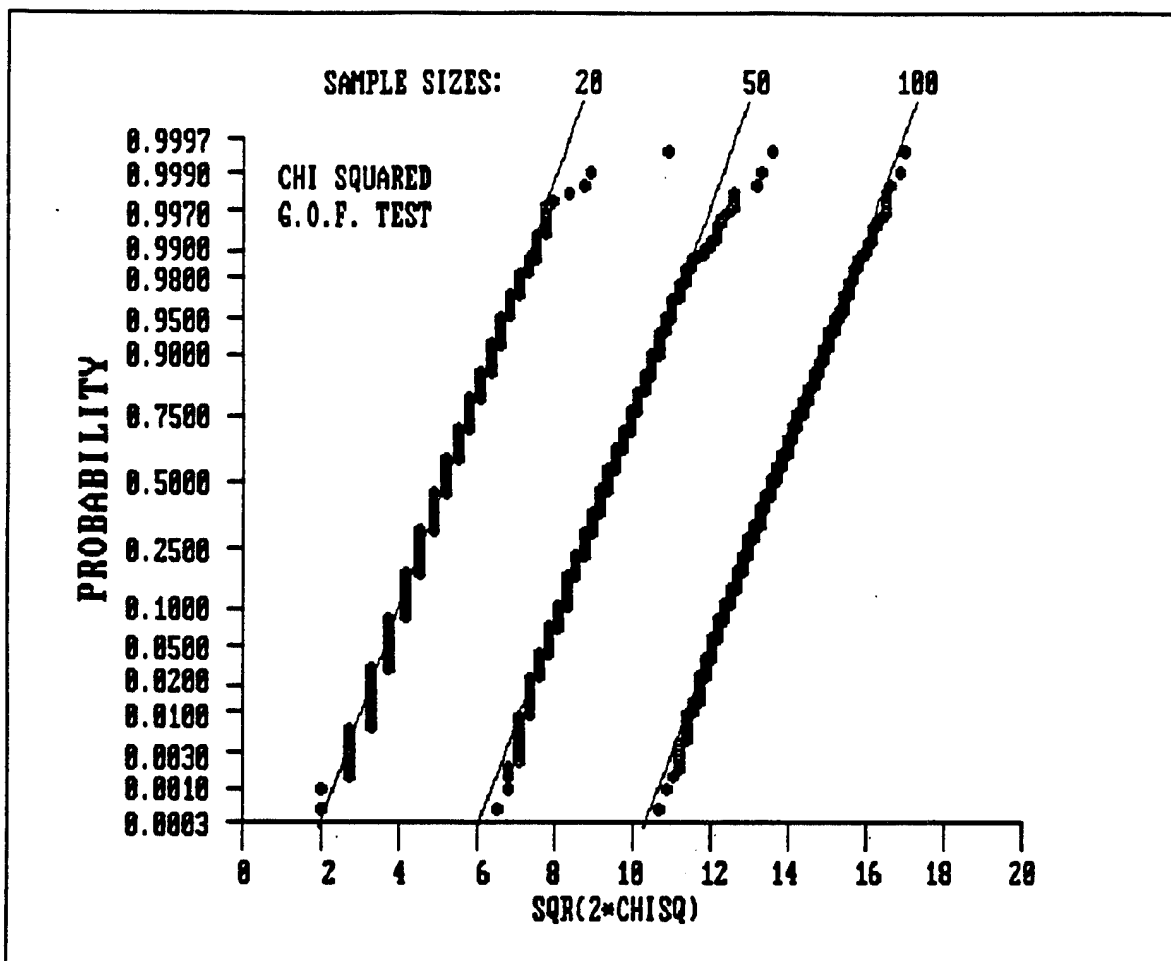


FIGURE II-11. Interpreting gof tests using  $n-3$  equal-probability zones where  $n$  is sample size. Plot also shows how deviations from normal form may not become apparent until a sufficiently large sample size is taken.

completely in Section 70.2, as an example of computer generated data from simulations of chi-squared goodness-of-fit tests. Each data point represents a simulation. The resulting simulated data turned out to be quantized at specific values (a small consideration) and to deviate from a normal distributions at the high extreme. Only after performing thousands of simulations did the deviations became apparent and it would have been unwise to 99.9% probabilities on the basis of fewer than the order of 1000 samples. As a general rule, unless there is strong theoretical or empirical evidence to justify the assumed probability distribution, when probabilities and confidences are quoted, the probabilities should not be less than the order of  $1/N_{eff}$  or exceed about  $1-1/N_{eff}$  where  $N_{eff}$  is the effective number of tested parts.

## APPENDIX II

### 70 Advanced Procedures.

70.1 Further examination of reasonability of data. We have seen that constructing probability plots is a first step in evaluating data. The plots can also be used to get estimates of relative within-lot and lot-to-lot variations and sometimes effective sample sizes. Though texts on probability theory have tests for specific problems, they cannot anticipate every complication that might arise and there is no replacement for examining probability plots. In what follows we will nevertheless suggest, for the reader with some familiarity with probability theory, some specific tests on the reasonability of data.

70.2 GOF (Goodness-of-Fit) Tests. GOF tests are described in almost every text on probability theory (e.g. Natrella<sup>1</sup>). Usually, a proper test requires that the variable space from minus infinity to plus infinity be partitioned into at least 5 contiguous zones and with at least 5 devices in each zone. However, when there is a small number of parts, these requirements may make the usual GOF test impossible and/or very insensitive to glaring problems. It was found, however, by Monte Carlo simulation that the test seems to work if the number of zones is as large as  $N-3$  even though this will mean that many zones will have less than 5 parts. FIGURE II-11 shows the distribution of chi-squared values for sample sizes of 20, 50 and 100 when the range of the normally distributed variable from minus infinity to plus infinity divided into  $N-3$  approximately zones of approximately equal probability. The "staircase" appearance of the distribution of  $\text{SQR}[2(\text{CHISQ})]$  derives from the fact that the values of chi-squared can take on only discrete values. Evidently, the chi-squared GOF test works after a fashion, even when the general rules for its validity do not hold. The curves of FIGURE II-11 may be used to evaluate the results of a chi-squared GOF test. (Note that the number of degrees of freedom is  $N-6$  when the test is done with  $N-3$  zones so clearly this test cannot be done with 7 or fewer parts.) As applied to the example of Section 60.3.1, the chi-squared was 44.5 yielding a 0.03% confidence that the data was drawn from a homogeneous normal population.

70.3 Sample Size Corrections. For this method to work, there must be approximately the same number of parts in each "sublot" of an inhomogeneous inspection lot. If the region of minus infinity to plus infinity is divided into a recommended number of  $N-3$  equal probability zones, the effective sample size,  $N_{\text{eff}}$ , may be calculated from,

$$N_{\text{eff}} = N * (N - 6.5) / (\text{Actual CHISQ})$$

As applied to the example of Section 60.3.1 with an actual sample size of 20, the chi-squared of 44.5 gives an effective sample size of 6.

70.4 Use of Confidence lines. If confidence lines representing one-sided tolerance limits are placed on a probability plot, the number of data items to the left of the line is a rough test of whether there is anything suspicious in the data. On the average, fraction  $C$  of the data items should lie to the left of the  $C$  confidence line. However, there are wide variations about the average.

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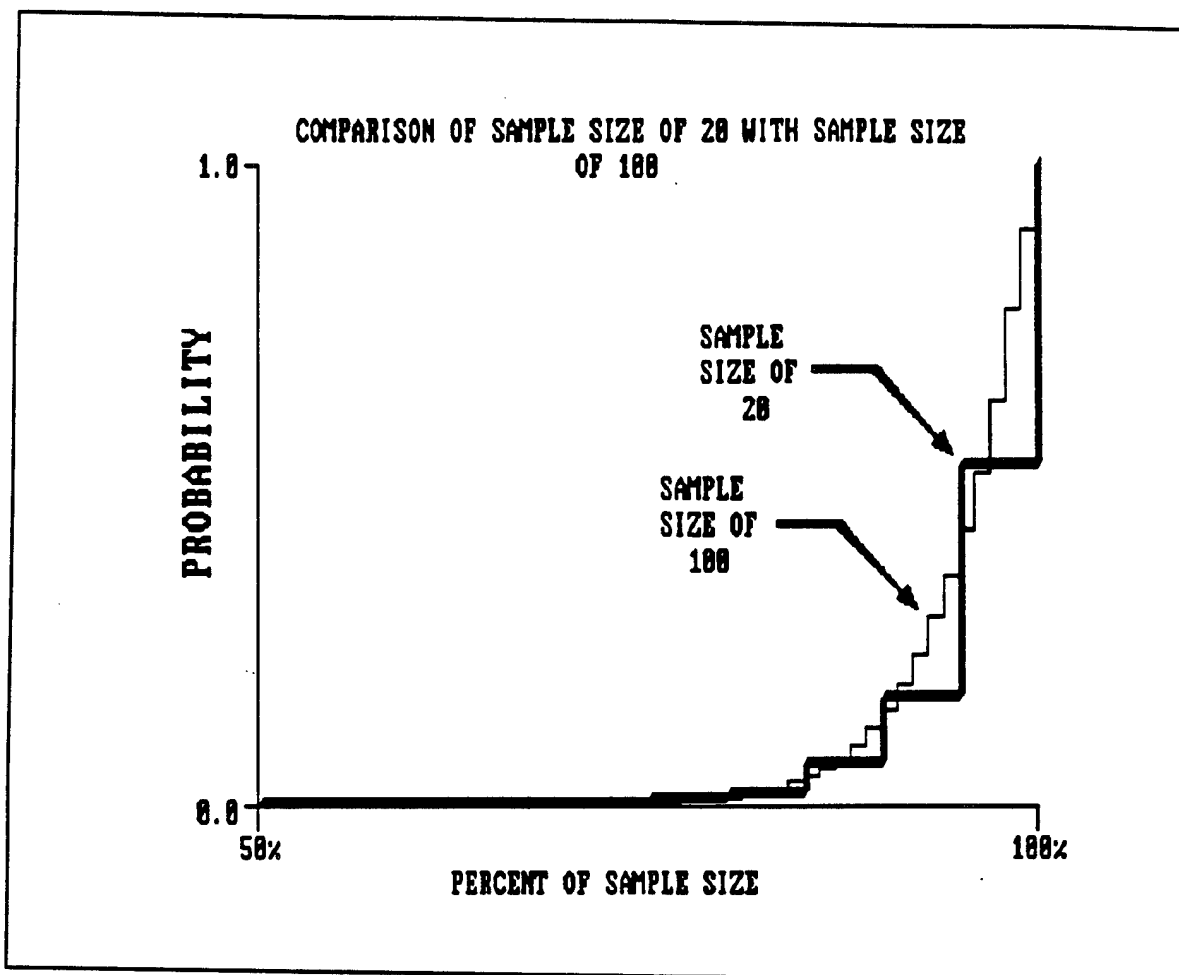


FIGURE II-12. Expected fraction of devices which exceed 90% confidence line. Sample sizes of 20 and 100.

Since an analytic calculation of exactly how this varies, a Monte Carlo simulation was performed. The probability that a given fraction of data items will lie to the left of the confidence line seems to be independent of the sample size as illustrated by the histogram of FIGURE II-12 for 90% confidence lines. We can conclude that if fewer than 60% of the points lie to the left of a 90% confidence line, for example, then the data is suspicious. FIGURE II-13 is a similar plot for 10% confidence lines.

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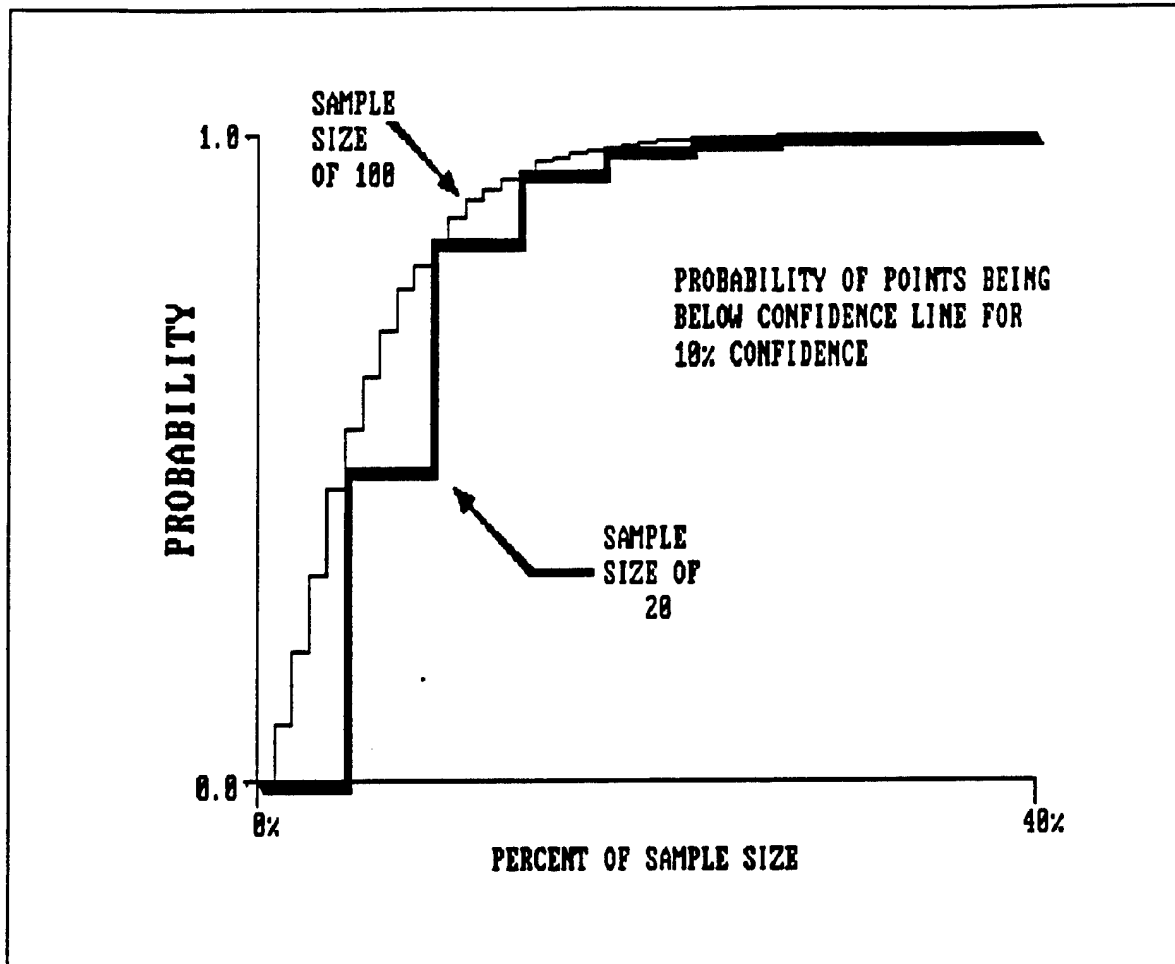


FIGURE II-13. Expected fraction of devices which exceed 10% confidence line. Sample sizes of 20 and 100.

## APPENDIX III

### BENEFITS OF OVERTESTING

There are significant benefits to testing at a greater radiation level than the specified radiation dose level (SRDL) that a system must survive. In brief, for a given required part survival probability and confidence level at the SRDL level, an overtest at X times SRDL will require a smaller sample size than the same test performed at SRDL. Thus, the costs of testing in terms of sample device costs and in terms of the shorter time required to do the tests on a reduced sample size can be substantial. In addition, overstress testing ensures that abrupt failures will not occur right at SRDL. It is also true that, for a given sample size, an overtest at  $X * \text{SRDL}$  will provide an increased part survival probability at SRDL. This latter case is discussed in the following paragraphs.

It is straightforward to calculate the part survival probability at SRDL from radiation response data obtained at  $X * \text{SRDL}$ . The procedure is to calculate an end point limit (RHEPL) or a derated parameter limit (DPL) (see section 5.2.3.6) from the  $X * \text{SRDL}$  data and then to use that DPL for the hardened circuit design at SRDL. Using the derated parameter limit obtained from  $X * \text{SRDL}$  data corresponds to having an increased part survival probability, P, at SRDL.

The following discussion, based on Iebo data, illustrates how the new survival probability, P, increases at SRDL when post-irradiation measurements are made at  $X * \text{SRDL}$  and SRDL. Assume, for this example, the following conditions:

SRDL = 10 krad(Si)  
Overtest is at  $X = 5$ , so  $X * \text{SRDL} = 50 \text{ krad(Si)}$   
  
Sample size  $n = 5$   
Confidence level  $C = 0.9$  at 50 krad(Si)  
Part survival probability  $P = 0.95$  at 50 krad(Si)

For these values of n, C, and P, the one-sided tolerance limit value,  $\text{KTL}(5, 0.9, 0.95) = 3.40$ .

Assume that the measured radiation response data is:

$\text{MEAN}(\text{Iebo}(50 \text{ krad(Si)})) = 33.22 \text{ nA}$   
 $\text{STDEV}(\text{Iebo}(50 \text{ krad(Si)})) = 5.876 \text{ nA}$   
 $\text{MEAN}(\text{Iebo}(10 \text{ krad(Si)})) = 13.88 \text{ nA}$   
 $\text{STDEV}(\text{Iebo}(10 \text{ krad(Si)})) = 1.580 \text{ nA}$

The derated parameter limit, DPL, at 50 krads(Si) is then:

$$DPL(50 \text{ krads(Si)}) = 33.22 + 3.40 * 5.876 = 53.198$$

and this DPL is to be used at 10 krads(Si). Thus

$$53.198 = 13.88 + KTL(5, 0.9, ?) * 1.580$$

and therefore  $KTL(5, 0.9, ?)$  must be 24.88. To obtain this KTL, the part survival probability must equal 0.999. Thus, in this example, the part survival probability has increased from 0.95 at 50 krads(Si) to 0.999 at 10 krads(Si).

A further example of the benefits of overtesting is shown in Table III-1 (ref. "Hardness Assurance and Overtesting," A. I. Namenson, IEEE Trans. on Nucl. Sci., NS -29, 1821, (1982)). The table shows how overtesting can reduce the number of parts that are subjected to an LTPD test with no failures as the acceptance criterion. We assume that the parameters are lognormally distributed, that the required part survival probability is 0.999, the maximum standard deviation in the logarithms is 0.83, and the confidence level is to be 0.90. Table III-1 lists the overtest level, sample size (the number to be tested at the overtest level with no failures allowed), and the LTPD (lot tolerance percent defective) probability. The differences are striking. To get the desired survival probability of 0.999 and the desired confidence level of 0.9, an LTPD test at SRDL requires 2302 parts to pass without a single failure, while an LTPD test at 10 \* SRDL only requires 5 parts.

Table III-1. Overtest level, sample size with no measured failures, and LTPD probability for a survivability of 0.999, confidence level of 0.9, with a maximum likely standard deviation in the logarithms of 0.83.

OVERTEST LEVEL	10X	5X	4X	3X	2X	1X
SAMPLE SIZE	5	17	29	60	191	2302
LTPD PROBABILITY	0.631	0.873	0.922	0.962	0.988	0.999